2016-03-01

Maximizing Virtual MUCAx Engineering Design Team Performance

Brett Randall Stone
Brigham Young University

Maximizing Virtual MUCAx Engineering Design Team Performance

Brett Randall Stone

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

W. Edward Red, Chair
Steven E. Gorrell
Shelli Sillito Walker
C. Greg Jensen
Christopher A. Mattson
Michael C. Richey
Peter Madsen

Department of Mechanical Engineering

Brigham Young University

March 2016

ABSTRACT

Maximizing Virtual MUCAx Engineering Design Team Performance

Brett Randall Stone
Department of Mechanical Engineering, BYU
Doctor of Philosophy

Teams of design engineers are increasingly working as members of virtual teams, or teams whose members are distributed geographically and communicate mostly through electronic means. In addition, emerging multi-user (MU) applications engage complementary teams in synchronous design activities. These new MU tools are changing the way engineers work together. Together, these factors have created a new and interesting environment in which engineering design teams must function.

The work presented here lays out two major themes that teams and their managers can effectively apply to organizing and managing MU teams: 1) teams can maximize their potential productivity by determining the optimal number of teammates for a given modeling effort and by implementing a profile and team formation system based on the principle of optimizing complementary team member characteristics; and 2) to minimize process losses, teams can implement effective strategies for working in a MU and/or virtual setting and they can use novel new MU tools that address portions of the product development process that have previously not been addressed with such tools.

It is my hope that these contributions can enable greater effectiveness and productivity among virtual engineering design teams as they strive to remedy many of the most pressing and dire issues facing humanity. By improving the way we work together, we can increase our ability to bless all of God's children.

Keywords: multi-user CAD, virtual teams, engineering design, teamwork

ACKNOWLEDGMENTS

Studying and working at Brigham Young University has been one of the great blessings of my life. In the effort to complete this research I owe a lot to a lot of people. First, I wish to thank my wife, Mallory, for her unending support and encouragement, as well as our son Tyler, who joined us part way through. Next, I must thank my parents, who have encouraged me as long as I can remember to do my very best in school and strive to be all I can - thank you for your sacrifices and love. I'd also like to thank Dr. Red, my adviser, for his continuous tutelage and guidance. Special thanks go to the directors of the AerosPACE project ("Development and Delivery of AeroPACE Capstone Project"), Dr. Gorrell and Dr. Richey (and Boeing) for funding as well as advice, mentoring, and the opportunity to work with and study the AerosPACE program. I am grateful to Dr. Sillito for the large amount of instruction, direction, and insight she offered, as well as Dr. Jensen, Dr. Mattson, and Dr. Madsen for their encouragement and support, and instruction. Finally, I wish to thank all the members of the BYU CAD Lab for their friendship, encouragement, and the wonderful environment they created. Thank you, Dave French for being a great desk-neighbor and role model, and thank you testers and undergraduates for working so hard on all the tests and experiments we ran.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

MU	Multi-User software applications that allow multiple users to simultaneously contribute
CAD	Computer Aided Design
MUCAD	Multi-User Computer Aided Design
CAx	Computer Aided “X” - any other computer aided application, such as Manufacturing
MUCAx	Multi-User Computer Aided “X”
API	Application Program Interface
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial System (used interchangeably with UAV)

CHAPTER 1. INTRODUCTION

1.1 Problem Statement

1.1.1 Teams and Virtual Teams in Engineering

Engineers and designers spend much of their time working in teams [1] [2]. Present trends indicate these teams will work in an ever more virtual and geographically distributed world [3] [4] [5]. The amount of time allowed for organizations to complete their work has also been decreasing [6]. To accommodate these shorter design cycles involving virtual teams of engineers and designers, researchers such as Wylczynski and Jennings state that the collaboration tools needed for these teams to be successful must drastically improve [3]. Red et al have also identified the need to replace restrictive, single-user engineering tools with simultaneously collaborative engineering tools that encourage, rather than impede, collaboration [7].

One powerful example of the evolution of engineering tools to meet this demand is the development of multi-user (MU) computer-aided engineering applications (CAx) like the NXConnect CAD system developed at by budgets under the BYU site of the National Science Foundation (NSF) IUCRC Center for e-Design [7] and Onshape [8]. Systems such as these allow designers to enter the same part at the same time as their peers and simultaneously contribute. These new norms of working with geographically distributed teammates using virtual tools that allow simultaneous contribution open up exciting opportunities, but also demand answers to serious questions.

For example, how can team members effectively communicate and collaborate in this type of situation? Virtual teams often face more difficult communication challenges than collocated ones [9] [10]. New or adapted communication and collaboration tools show promise for improving team performance [11] [5] but will require further development. Another question is how managers of multi-national engineering organizations can know they have the optimal combination of personnel assigned to a project when it is impossible to personally know all the individuals in their organization [12]. Great potential to optimize the organization and performance of teams exists if managers can access the right data and the right tools to use that data [13].

For engineering design teams to realize the full potential of working in a virtual, geographically distributed, cross-functional, MU design environment, it is necessary to better understand how to form effective engineering design teams and to enhance their ability to communicate and collaborate after they are formed.

1.1.2 Principles of Team Performance

Teams are made up of individuals who share responsibility for an outcome [14], depend on each other and share common goals [15] [9]. Some of the potential advantages of teamwork include creating synergy, cost savings, and a greater variety of viewpoints, experiences, and expertise [12] [9] [16], to name just a few. Teamwork is considered an essential skill in engineering and the product development process [17] [18] [19]. To what degree a team achieves its potential depends on various factors. A general equation from Steiner is shown in 1.1:

$$Prod_a = Prod_p - Losses_{pcs} \tag{1.1}$$

where $Prod_a$ is actual productivity, $Prod_p$ is potential productivity, and $Losses_{pcs}$ are losses from process [20]. It logically follows that teams which maximize potential productivity and minimize process losses will maximize their actual productivity. The purpose of this research is to maximize virtual engineering design teams' actual productivity and will explore methods and principles of doing so by maximizing potential productivity and minimizing process losses.

CHAPTER 2. BACKGROUND

2.1 Introduction

The Steiner equation introduced in equation 1.1 provides a simple and yet powerful lens through which to view teamwork. Steiner was influenced by the work of an agricultural engineer named Max Ringelmann who worked nearly 100 years earlier in France [21]. Ringelmann found that individuals (men, horses, or oxen) who pulled on a load all pulled hardest when working alone. When acting in pairs or in groups of increasing size, their output tended to drop off and eventually settle at a percentage of their original, individual output. This fact allowed him to estimate an optimal team size for this type of activity of about seven or eight individuals.

In studying this phenomenon, Ringelmann attributed the losses he observed to two factors: motivation and a failure to precisely coordinate the application of their efforts. In the view of Steiner's equation, they are both "process losses". Focusing on the coordination loss, Ringelmann noted that some efforts by groups to mitigate such losses already existed, such as singing to coordinate when to pull. One can also imagine the beating of a drum on a ship propelled by oarsmen.

Ringelmann took care in his studies to ensure comparisons between different groups were of men or animals of comparable size, strength, and fatigue levels [21]. This demonstrates that he understood the importance of the other factor in Steiner's equation, namely "potential productivity". A team made up of individuals of higher skill, strength, or other relevant ability can outperform teams of lesser ability, even, to a point, when experiencing process losses.

Although Ringlemann's work focused primarily on motivation and coordination losses, Steiner's equation also accounts for a third type of process loss: namely, ability losses. Losses related to team member abilities include dominance, production blocking, information overload, evaluation apprehension, and others [22]. Littlepage et al. point out that a team's performance depends upon both the level of member talent, skills, and expertise, and the group's ability to identify/recognize the abilities of its individual members. A team which is unable to do so will suffer from this third type of process loss. These kinds of losses subtract from a team's potential productivity, which depends in part on the resources (including relevant knowledge, abilities, or skills) the team can bring to bear on the task.

If the phenomena of decreasing individual output in teams due to process losses, attempts to mitigate them, and related topics such as optimal team size were limited to agricultural situations, or even just situations of applying physical force, this might be a much less interesting subject. However, these effects appear in areas far removed from the farm field. Brooks explains that in software construction projects, by simply adding people to a project, the time required to complete the project first decreases, then levels off, then will very often increase as more people are added [23].

Brooks argues the reason for the decreasing and eventual negative effectiveness of adding teammates is due to communication overheads. Each new person added to the team must first be trained, and then coordinated with. The amount of needed coordination depends on the type of task. If the task is something like picking berries, requiring little to no communication to coordinate, the task is said to be perfectly partitionable. Given a very large berry patch, berry pickers could be added continuously with no loss in the increase of number of berries picked for each worker added. However, Brooks argues that most software engineering tasks are much more complex, involving intricate interrelationships that require extensive communication between team members to ensure a functioning product. In the light of the losses discovered by Ringelmann when attempting to accomplish much simpler tasks, the losses in teams portrayed by Brooks seem quite reasonable. Other, more recent studies have confirmed the general idea that individual output tends to decrease as group size increases [24].

2.2 Virtual Teams

Despite the great differences in the previously mentioned teams, from farming, to oarsmen, to software engineering, they all had something in common. Even in the time period when Brooks wrote his seminal work on software development teams (the 1970's), most teams worked in the same physical location and coordinated their work in-person. At worst, they were close enough to schedule face-to-face meetings on a regular basis. More recently, however, that situation has changed significantly.

Virtual collaboration, or members of teams working together from different geographic locations via internet or network based tools [10], is an increasingly common and important form of collaboration in many fields of work, including engineering. In a survey of hundreds of private and public organizations, WorldatWork found that in 2013 more than one third of organizations in the manufacturing, consulting, professional, scientific, and technical fields offered positions for employees to work remotely full-time. Roughly half of organizations in those fields also offered positions which required virtual collaboration at least once a week [4]. Golden and Raghuram cite various sources showing that the number of workers using virtual means to collaborate has increased and will likely continue growing at around 30 percent per year [25]. Other researchers agree, adding that most large companies use virtual teams in at least some way [26]. Some researchers even see virtual teamwork as a necessity of the modern workplace. Salomo et al. argue that in order for new product development teams to compete successfully in a global marketplace, organizations must leverage the diversity of experiences, cultural sensitivities, and perspectives a geographically dispersed virtual team can offer [27].

Concrete evidence of this shifting way of doing work can be seen in industrial practice. In a 2003 study of companies in the engineering, procurement, and construction industry, for instance, over half the companies surveyed used virtual teaming in at least some of their projects [28]. Nearly every company surveyed believed use of virtual teams would increase considerably or become routine business practice over the next five years from the time of the survey. In the automobile manufacturing industry, by the 1990's, the percentage of an automobile that was outsourced had risen to between 40 and 80 percent, and engineers estimated that 70 percent of their time was spent working with suppliers [29]. Outsourcing of this type, with suppliers, manufacturers, and marketers is, according to Stough et al., a type of virtual teaming which allows companies to obtain specialized expertise as well as reduction in cost [30]. In the commercial aerospace industry, Boeing's 787 offers another example. A large majority, 65 percent, of the new Dreamliner is supplied to Boeing by dozens of other companies located across the globe [31]. Engineers from supplier companies and Boeing are required to work together at unprecedented levels across great distances to generate designs, manufacture, and assemble the aircraft, representing an increasingly complex set of technical and social systems (or "sociotechnical system") which must both be optimized to achieve ideal $Prod_a$ [32].

French et al., performed a study of nine different engineering companies in fields such as aerospace, defense, energy, manufacturing and medical and found that nearly all these companies actively use tools common to virtual teams, such as instant messaging and screen/application sharing tools [33]. The fact that the teams they studied were mostly collocated teams, yet still use these tools, may suggest that in the modern engineering workplace, all teams share elements of virtual teaming.

2.3 Multi-User Tools

A particularly important development for virtual teams in the engineering field is MU Computer Aided Design and other applications (MUCAD or MUCAx). These are an important new set of tools that are being developed primarily by researchers at the Brigham Young University (BYU) Site of the NSF Center for eDesign [1, 7, 34, 35] as well as companies such as Onshape [8]. These tools allow multiple engineers, designers, analysts, managers, or others to access and manipulate models simultaneously from different computers or other devices. All contributors can see each other's edits to the model in real-time. NXConnect, a MU version of the ubiquitous Siemens NX CAD tool, has been developed at BYU and allows users to work together in a way that could demonstrate the future of virtual engineering design teamwork. MU versions of other types of engineering tools have also been developed, such as CUBIT-Connect, which is a MU pre-processing software tool used in finite element analysis [36] [37].

If virtual teams are significantly different than traditional teams, virtual engineering design teams using new MUCAD or MUCAx tools, are more different still. While it is not uncommon for virtual teammates to email each other documents to review or even check a file out from a repository (such as a Product Lifecycle Management or PLM system) to work on, until very recently it was rare to work *concurrently* via electronic means on the same workpiece (be it a word-processing document, spreadsheet, 3D model, or other). Google Docs may be the first example many people think of with regards to a tool which enables concurrent electronic work [38]. In the decades that have past since engineers moved from large, open spaces with drafting tables into more isolated cubicles with desktop computers scattered around the world, engineering design teamwork has certainly undergone some significant changes.

2.4 Conceptual Framework

The question then, is whether the equation formulated by Steiner can be effectively used to describe these modern teams, especially ones that operate using new, MU tools that enable real-time application sharing and collaboration. Asking that question also asks whether the effects described by Ringelmann are the same, more, or less pronounced in modern, virtual, engineering design teams. Research by others, as well as experience from experiments run here at Brigham Young University shed light on that topic.

2.4.1 Literature

Using technology to collaborate changes the way teams communicate [9]. Levi also explains that the differences between standard, in-person team communication and collaboration carried out exclusively via electronic means are often related to communication problems in teams causing emotional frustration. While Levi explains that many of the difficulties of digital collaboration shrink over time as teams learn how to operate in a non-native communication mode, Driskell et al. also state that virtual teams whose members have never worked together before struggle to develop strong team commitment and pride [10]. They also found that technological mediation had a generally negative impact on group cohesiveness. Levi adds that conflict can be more difficult to resolve in virtual teams [9]. Experiments have shown that virtual groups often take longer to reach decisions [26]. Dyer et al. suggest that leaders of virtual teams should plan to spend 50 percent more time managing a project run by a virtual team than for the same project run by a collocated team [39]. Parks and Sanna show that individual satisfaction with the group is lower for virtual groups than for face-to-face groups [40]. De Pillis, in a study of nearly 70 in-person and virtual teams found that not only was average performance of virtual teams lower than in-person teams, but team members were more likely to become “dead-beats” or “deserters” on virtual teams than in-person teams [41]. Finally, Dyer et al., possibly explaining Levi’s point that the negative effects of virtual teamwork often fade over time, states that one of the largest challenges for virtual teams is to do a good job deciding which virtual collaboration tools to use for which collaboration tasks [39].

The news is not all bad though, for virtual teams. Besides the obvious (and attractive) benefits of avoiding expensive, time consuming, and polluting travel, and enabling team members to "meet" from many more locations, Hertel shows that virtual groups perform better at brainstorming and other "generating" activities than collocated groups by preventing motivation and coordination problems [26]. There is also some reason to believe that as more young people, used to playing collaborative games like Minecraft, enter the workforce that their experience with virtual collaboration could mitigate some of the negative effects mentioned previously [42]. The same researchers point out that many of the same management and organizational structures from collocated teams appear to be effective in virtual teams. It should also be acknowledged, however, that despite the new generation's virtual savvy, examples abound of lower emotional intelligence when using such tools [43, 44].

From these sources, it can be concluded that virtual teams have their own nuances of operation, and at least while learning how to operate effectively, may be significantly more difficult than collocated teamwork. However, on the whole, virtual teams share most of the same basic attributes, benefits, and challenges as traditional, collocated teams [15]. While conflict resolution may be more complicated on a virtual team, conflicts still arise. Decision-making may take longer, but decisions must still be made. And while communication and data sharing may take place via different mediums, it must still take place.

2.4.2 A Multi-User Modeling Competition

Still, none of the sources cited above treated teams using the type of new, MUCAx tools explained earlier. To provide more evidence that examining MUCAx teams through the lens of Steiner's productivity equation is justified, results of a MU modeling competition and comparison with single-user modeling are briefly presented.

A competition was held on the Brigham Young University (BYU) campus to which all interested students were invited to participate. The competition involved teams of three students which were each given 25 minutes to model a small sheet-rock cutting depth guard (see Figure 2.1)

Figure 2.1: Photograph of cutting guard which served as the basis for the competition

using the MUCAD system NXConnect. Students were seated with their teams at a table as seen in Figure 2.2.

Competitors were not made aware of what they would be modeling until their team began the competition. Each team was given five minutes of standardized instruction regarding the use of NXConnect and the rules of the competition. A sheet of letter-size paper with instructions and some key dimensions was given to each participant (see Figure 2.3).

Before the competition was held, engineering students enrolled in an introductory CAD course also completed the same model as part of a regular course assignment. As part of the assignment, they each recorded the time spent to complete the model and were encouraged to complete it as quickly as they could.

Figure 2.2: Photograph of two teams competing simultaneously at different stations with proctors monitoring and taking notes

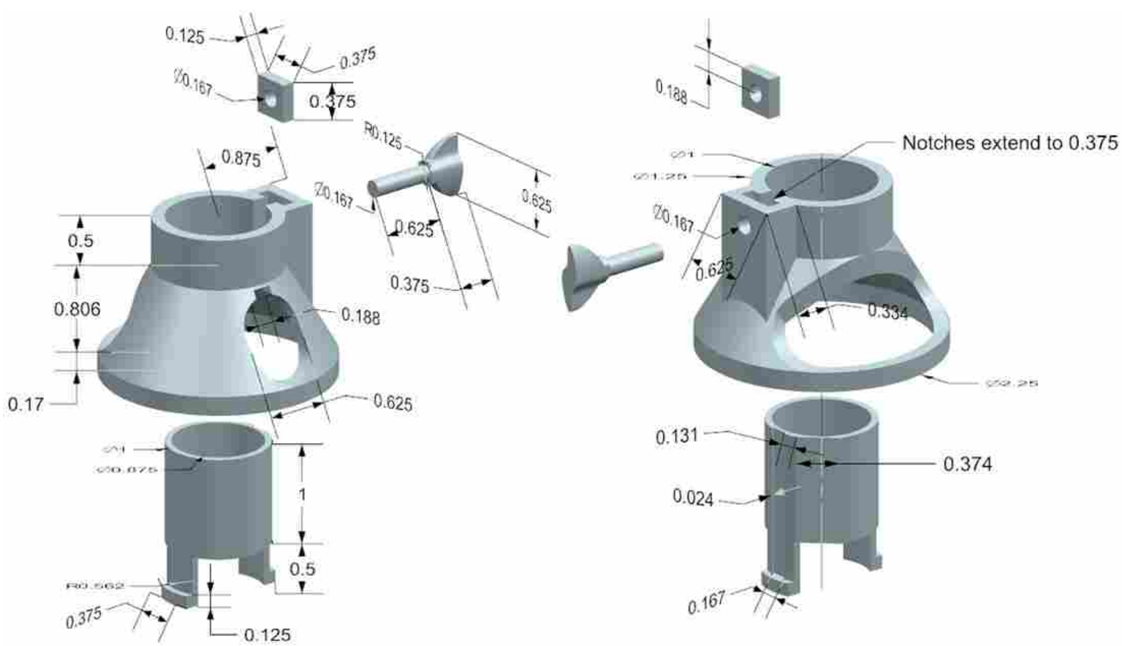


Figure 2.3: Graphic given to competitors at start of 25 minutes of competition

CAD Modeling Task Description

Modeling the cutting guard, whether as a single-user or as part of a MU team, involved a variety of CAD features ranging from very simple to moderately difficult (in the context of a university setting). For example, the nut that allows the sliding depth gauge mechanism to be locked is a very simple portion of the design. One method to create it would be to sketch a simple square and a circle inside it, then extrude that sketch (assuming that threading would be indicated in a drafting document). An example of a more complex feature set could include the viewing window cutout on the side of the guard's largest piece. A common method of accurately modeling this portion of the design usually involved using splines and/or projecting negative extrudes from more than one angle through the guard.

We modeled the cutting guard many different ways on our own and with a few pilot groups to benchmark how long we should expect a team to require to complete the model and if the cutting guard was a good subject for the competition. Based on our experience, we felt that the diversity of both simple and relatively more complex portions would provide a good level of "granularity" for determining the level of proficiency of each team in the time allotted. That is, in 25 minutes, the best teams would have just about enough time to finish the project, while the rest of the teams would have only advanced to a certain point that would be related to their level of proficiency.

Participants and Demographics

Of the 63 students who competed (21 teams of three), 50 completed the post-competition survey. Of those students who completed the survey, 47 provided their major. It is acknowledged that the size of the sample limits the conclusions that can be drawn. However, as will be seen, the study still provided interesting and important results. The great majority of the students participating in the competition were studying mechanical engineering (40). Four were manufacturing engineering technology majors, one was civil engineering, one electrical engineering, and one had not yet declared a major. Only five females participated, perhaps correlating to the typically low numbers of women in the aforementioned majors [45].

The great majority (86 percent) of the survey respondents had taken BYU's mechanical engineering introductory course on engineering graphics in which a student learns to use one of the common CAD packages, such as SolidWorks, CATIA, or Siemens NX. Only 26 percent had taken the advanced engineering graphics course (a technical elective, not a required course), and only about four percent had taken other related, advanced courses. A few students (12 percent) also reported having had experience outside the university using CAD, such as in an internship, during high school, or for extra-curricular projects or hobbies.

Set-Up and Logistics

The competition was held on two different days, a Tuesday and a Thursday, during the Fall semester of 2014. In the lobby of one of the engineering buildings on BYU's campus, two groups of computers were set up for the teams to model. Trained student proctors from our research lab recruited, registered, and proctored the competition with assistance from graduate students and faculty. An online survey tool, Qualtrics, was used to administer the post-competition survey.

Each table of three computers that were used for modeling during the competition were arranged with two computers next to each other on one side of a table and the third across the table, making an L shape. Although it was not uncommon for two teams to be modeling at the same time, it was rare for two teams to start at the same time and teams were not allowed to interact with each other or observe each others' modeling techniques.

Students were recruited via email announcements, posters, digital signage, in-class announcements, and in-person recruiting at the event. All participants were asked to sign an Institutional Review Board (IRB) release form as well as photo, video, and audio release forms. Incentives for participation in the competition included refreshments for participants and prizes for the members of the winning team (remote control quad-copters). As well, one instructor offered extra credit in his advanced engineering programming course for participation in the competition.

Data Collection

An expert panel of three judges was selected to judge the competition. These volunteer judges, who were not involved in this study, have significant experience using CAD in industry and academia. After the competition this panel was presented with one 11" x 17" sheet per team with standardized views of each part modeled by the team. Three representative models completed by the single-user students from the introductory CAD course (not completed as part of the competition) were included among the competition team models to provide comparison with the MU team models. Individual, team, and teammate names were removed from the sheets and random sheet numbers were assigned in order to eliminate any possible judging bias.

After a brief training in which the judges were shown an example of a "gold-standard" sheet with a complete, ideal model, the judges used a standardized rubric to judge each model based on various qualities such as completeness and quality of modeling. Meanwhile, competition participants were asked to complete the online, post-competition survey that included questions regarding their previous experience with NX and/or NXConnect, other CAD software, how well they knew their teammates before the competition, and various other questions, including the PSVT:R (Purdue Spatial Visualization Test-Visualization of Rotations). To incentivize survey completion, participants were advised that only those participants who completed the survey would be eligible for the prize given to the winning team.

Score Adjusting

Given that NXConnect is research software and undergoing active development, bugs exist in the software. The version of software used for the competition in particular had an unforeseen bug that caused certain problems. All teams experienced these errors but in varying amounts and severity. These bugs and delays were not caused by a user's lack of experience or skill. Since these errors greatly affected some teams' performance, an adjustment to the judges' score was implemented based on the severity of the bugs.

Initially the need for an adjustment was uncertain, and so the video recordings of each teams' modeling were examined. When a bug appeared, the severity of the error was assessed. Once the bugs were counted and severity assessed for each team member (one video recording was created for each teammate), an average was calculated for the entire team. Large variance among teams' average bug severities supported the implementation of an adjustment.

Team bug severity ranged from 1.5 to 19.5, with an average of 8.11. To eliminate any effect bug severity had on the ability to objectively compare team scores, the severity of errors experienced by each team needed to be adjusted (and carry each team's score with it) to be at the average bug severity. This meant teams who had high bug severity had their scores adjusted up,

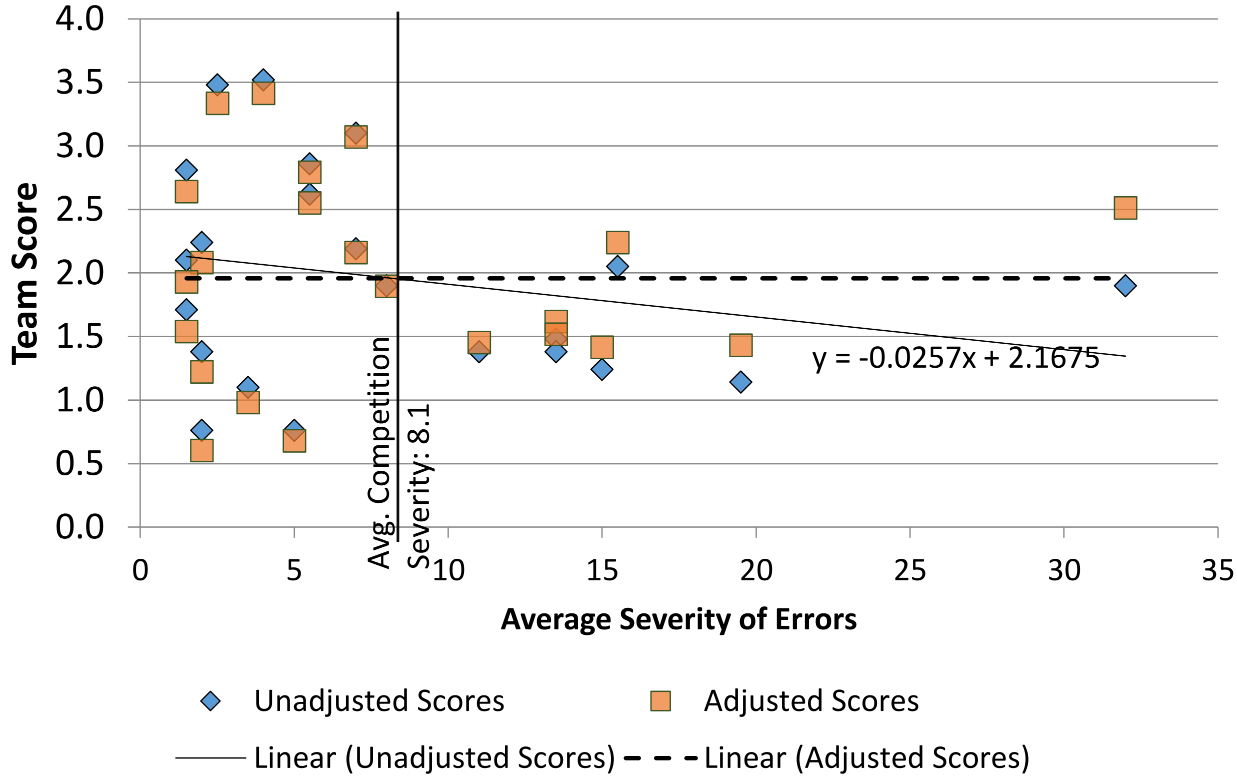


Figure 2.4: Plot of scores before and after adjustment vs average error severity

and those who had low bug severity were adjusted down. To apply this adjustment, a plot (see Figure 2.4) of team score vs. team average bug severity was generated, and a best fit line was plotted. The slope of this best fit line was used to generate a formula for adjusting team scores:

$$Score_{adjusted} = Score_{raw} - 0.02567(S_{CA} - S_T) \tag{2.1}$$

where $Score_{raw}$ is the score each team received from the judges before applying the adjustment, -0.02567 is the slope from the best fit line, S_{CA} is the average bug severity experienced across the entire competition (a constant), and S_T is the bug severity experienced by a given team (calculated from the average of all that team's members). This enabled teams' scores to be adjusted linearly with the same slope of the best fit line until they reached the point of average bug severity for the entire competition, effectively "leveling the playing field" for all teams. With these new, adjusted scores, a plot of adjusted scores vs. team average bug severity showed that a new best fit line was flat, thus achieving the goal that bug severity not correlate with scores.

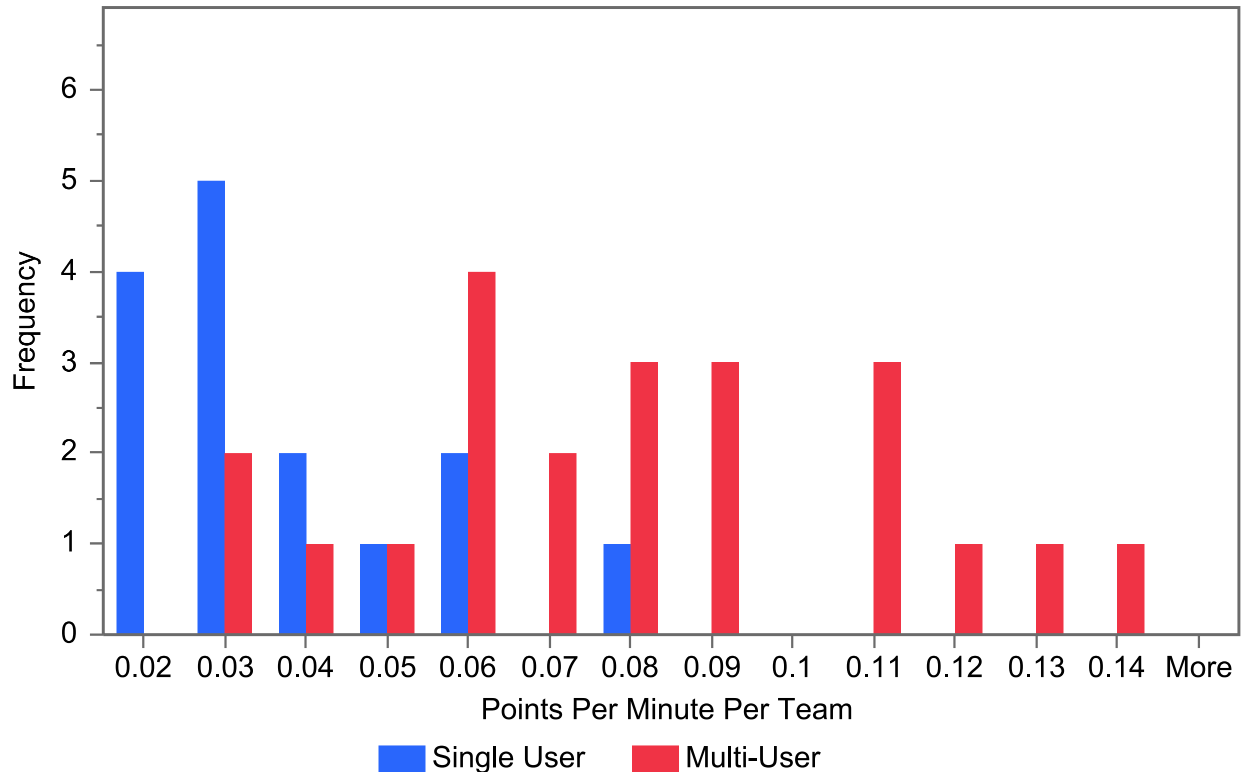


Figure 2.5: A comparison of the effectiveness of Single User and MUCAD teams based on calendar time, or points per minute per team. Single User values are shown on the left of each bin, MU team values on the right.

MUCAD Vs. Single-User Scores

In this evaluation we consider two different types of time: calendar time and man hours. Calendar time is treated here as the time a customer or recipient of the work must wait for completion, and man hours is treated as the total cumulative time the team took to finish, or the time an employer would pay for in labor costs.

Figure 2.5 represents the comparison between MUCAD teams and single user teams. A "team" here is treated as anyone working on the same assembly. Single user teams were made up of one person (from the introductory CAD course). The MUCAD teams were made up of three people who participated in the competition. Points per minute for both single user and MUCAD teams were calculated by dividing the team score by the calendar time required to complete the model:

$$P_{pm} = \frac{P_t}{t_c} \tag{2.2}$$

where P_{pm} is points per minute, P_t is a team's score (points), and t_c is the time required to complete the model. For the single-users this time varied, while for the MUCAD teams, this was the time limit of the competition (25 minutes).

We assumed that most of the single users arrived at a similar level of model completion, or would have scored about the same as the single-user models that were judged along with the competition models because they had no time limit to finish their CAD project. This assumption was substantiated by inspection of their models. Given this assumption, single users' P_{pm} was calculated by first taking the average of those single users whose parts were scored (n = 3). Then, that score was divided by each single user's time to complete the part.

Using this method to measure the two groups, the MUCAD teams performed better than the single user teams. The points per minute per team for MUCAD teams was, on average, more than twice that of the single user teams (single user average P_{pm} = 0.033, MUCAD team average P_{pm} = 0.0753). Holding the quality of the model constant, the fastest calendar time option appears to be MUCAD teams. As we can see in Figure 2.6, some MUCAD teams demonstrated significant improvements in performance (as measured by P_{pm}) compared to single user teams, while other MUCAD teams performed more poorly than some single users.

Figure 2.6 represents the comparison between the effectiveness of MUCAD and single user individuals. Points per minute per person was found by taking the total score, dividing it by the total time taken, by the number of people on the team:

$$P_{pmpp} = \frac{P_t}{t_c n_t} \tag{2.3}$$

where P_{pmpp} is points per minute per person and n_t is the number of members of the team. The MUCAD individuals performed moderately less well than the single user individuals on average (single user average P_{pmpp} = 0.033, MUCAD team member average P_{pmpp} = 0.0251) . However, as can be seen in figure 2.6, the single users are more widely distributed than the MUCAD team members, whereas the MUCAD are more tightly grouped, perhaps suggesting higher predictability in time to perform a given task.

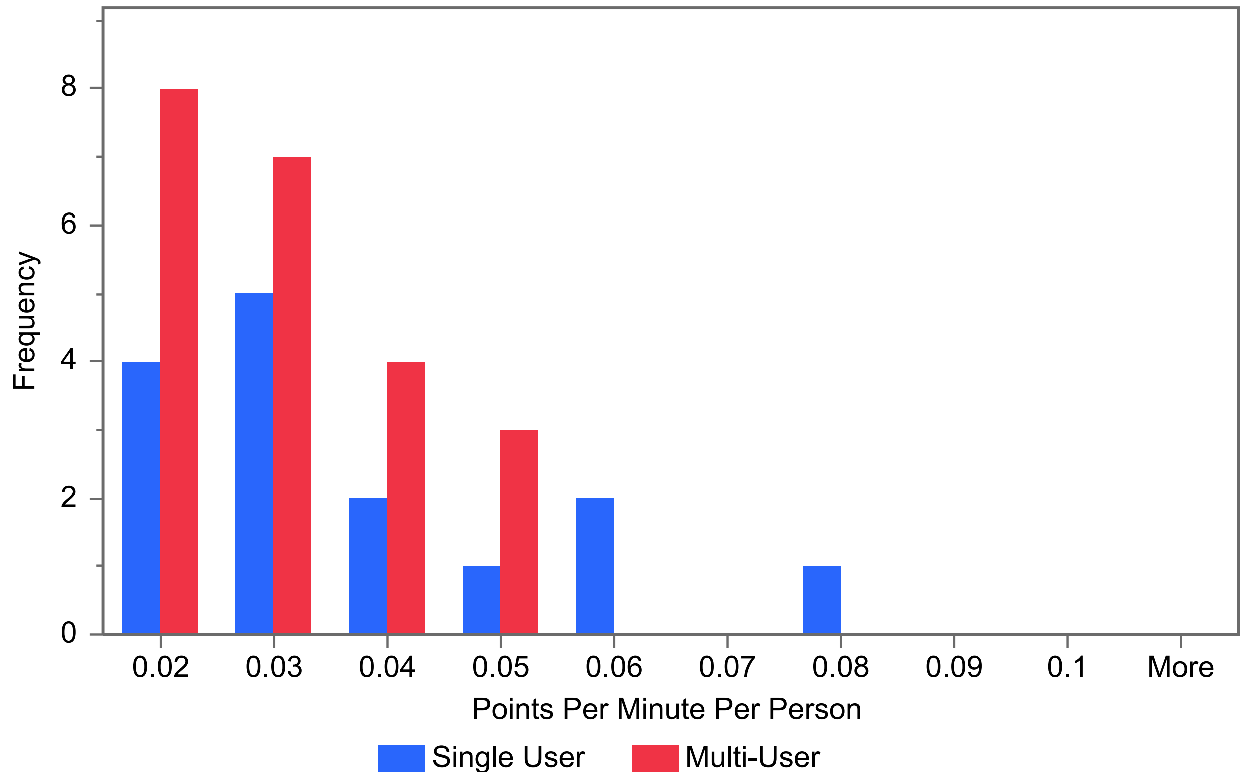


Figure 2.6: A comparison of the effectiveness of Single User and MUCAD individuals in man-hours, or points per minute per person. Single User values are shown on the left of each bin, MU team values on the right.

The fact that MUCAD team members' average contribution to team performance is slightly lower than the average single user contribution harks back to Ringelmann's studies of application of force by teams on farms. In fact, it is interesting to note that in Ringelmann's original work, he calculated, based on his experiments, that for a team of three workers, the usable work output per worker was about 0.85 of a single worker in isolation. The data from the MUCAD modeling competition, when comparing teams of three to single users gives a similar ratio:

$$\frac{P_{pmpp,MU}}{P_{pmpp,SU}} = 0.76 \tag{2.4}$$

Where $P_{pmpp,MU}$ is points per minute for MUCAD team members, and $P_{pmpp,SU}$ is points per minute for single users.

As well, observing figures 2.6 and 2.5, one can make a strong argument that the effects of factors from Steiner's equation are evident. Different teams, made up of different people with different levels of skill (affecting team $Prod_p$) and varied collaborative strategies, including communication habits (affecting team $Losses_{pcs}$), result in some teams producing very high quality work, and other teams functioning much less effectively, even less effectively than some single-users. Thus, from applying force to 19th century farm equipment to working as part of a 21st century MUCAD team, it appears that Steiner's equation provides an effective, broad model for describing actual team performance and the factors that affect it.

Given the evidences listed above from both the literature and analysis of the experiment, it seems clear that virtual teams of engineering designers, including those employing MUCAx tools, can still have their performance described by the Steiner equation, even if the exact characteristics affecting their potential productivity have evolved and the factors affecting process losses now also include the digital tools used to collaborate among teammates. For that reason, a review of the literature regarding both factors affecting potential productivity of teams and those influencing process losses is described below and considered throughout this research.

2.5 Literature Related to Maximizing Potential Productivity

2.5.1 Team Size Determination

Both Hackman and Dyer et al. assert that team size is one of the critical factors that affects a team's potential to perform, stating that the number of team members should ultimately be determined by the nature of the task [39, 46]. Parker, who researched cross-functional teams in various fields, agrees, and argues strongly for generally smaller teams [16]. Despite the apparent simplicity of the idea and its importance, Hackman has estimated that fewer than 10 percent of executive teams can even agree as to who is actually on the team [47]. He also agrees with Dyer and Parker that small teams (about 10 members or fewer) are better than large teams.

In the field of engineering design, previous research, including the study explained above, shows that multiple users simultaneously working on a CAD part in parallel can significantly decrease the time it takes to complete the part and increase the quality of the collaboration. We have found that as more users are added, the time to complete the part tends to decrease. However, there is a point at which adding more users no longer decreases the time to completion, and in many cases, increases the time to completion [48]. There is an optimal point at which either increasing or reducing the number of users increases the design time. This point, which is specific for each CAD part, is what we call the optimal number of simultaneous contributors. Although previous research alludes to the fact that there exists an optimal number of simultaneous contributors for a specific CAD part, no one has attempted to determine what factors influence this number. Nor has anyone determined any methods to predict this optimum number.

Brooks addresses attributes of teams of various sizes and task types [23]. For teams working on tasks which require communication, Brooks argues that adding more members to the team does not improve the time to task completion in a linear fashion. Instead, he shows that each time a new teammate is added, the marginal improvement decreases. For tasks with more complex interrelationships, such as the software development projects he studied, a point comes at which adding team members begins to negatively affect the time to completion. Hepworth et al. demonstrated similar results in a MUCAD environment [48].

2.5.2 Team Member Selection

Multiple methods for organizing teams exist. Ad-hoc methods, such as allowing students to self-select their teams, or administrators randomly assigning teams have been common, even in military settings [49]. However, as pointed out by Layton et al., these methods often lead to sub-optimal results [50].

For example, a leader may simply assign responsibilities to group members based on his/her best judgment, without any consultation. Another common method involves leaders asking for volunteers for positions and then quickly judging the volunteers based on their capabilities and the needs of the position(s).

Especially in the context of a geographically distributed, virtual team, these mostly ad-hoc methods suffer from various shortcomings. As Hackman points out, the composition of a group, such as an Integrated Product Team (IPT, aka "sub-team"), is the most important condition affecting the amount of knowledge and skill the group can apply to the task [46]. As well, various authors have promoted the importance of teams developing a "Shared Mental Model" of the project they are working on together [11,13,51]. Moreland et al. explain further that it is not only important for a team to have a shared mental model of the project they are working on, but also to have a shared mental model of the team itself and the teammates who make up the team [13]. Knowing who knows what and who is good at what are important parts of what Moreland et al. define as "Socially Shared Cognition". Citing extensive evidence, they state that despite the difficulties of gathering the data needed, when a group knows who knows what and who is good at what, the organization can more optimally allocate its most important resources: its people. It is easy to see how in a virtual team, whose members are geographically far apart, building these sorts of mental models is even more difficult.

A thought experiment, along the lines of that suggested by Moreland et al. elucidates this point further. Imagine a new team whose leader knows very little about the members of the team, or at least about certain members of the team, such as would likely be the case of a virtual design team. The potential shortcomings of organizing this team using traditional, ad-hoc sub-team organization methods could include the following, broken down by whether the shortcoming originates with those volunteering for positions or with the team leader (see Table 2.1 and Table 2.2 below).

As can be seen by examining the potential problems that can result from an ad-hoc team organization method, many of these problems have to do with a lack of knowledge regarding members of the team and low levels of trust among team members, demonstrating how the ad-hoc method can make forming a shared mental model of the team more difficult. Kramer and Tyler substantiate this idea in their work on trust in organizations [52]. They discuss how groups whose members don't have time or resources provided to help teams get to know each other's qualifications and interests tend to rely on importing expectations about broad groups of people based on past experience or stereotypes. Depending on this type of information does not provide the quality of data needed to build a reliable shared mental model of a team.

Woolley et al. have shown that teams with members whose skills are complementary perform better than teams with incongruent or homogenous skill-sets [53]. One example from outside a professional context of systems that enable users to automatically combine individuals to form more optimal teams is Futwiz, which allows players of the video game 'FIFA 15' to select an optimal squad of futbol players based on desired characteristics [54]. Even dating websites such as Match.com employ techniques such as reverse matching to help users find people who are interested in someone like themselves [55]. In industry, companies like Action and Influence offered services such as "Team Science" [56]. And in academia, CATME provides a free service which

Table 2.1: Potential problems that may occur with ad-hoc volunteer team formation

Volunteers	
Problems	Possible Causes
Not volunteering for a position they are truly motivated to pursue	Nervous or uncomfortable about volunteering for position in front of peers
	Not given sufficient time to understand position, consider opportunity, or weigh options (as in a group meeting when a leader asks for volunteers before listing and describing all positions)
Not volunteering for a position they are,truly qualified to hold	Not being sufficiently aware of the responsibilities of the position the ad-hoc description offered may be insufficient,or unclear
Volunteering for a position they are NOT truly motivated to pursue	Desire to fit in with group, be seen favorably by others, be seen as a contributor
	Misunderstanding the responsibilities and requirements of the position
Volunteering for a position they are NOT truly qualified to hold	Desire to fit in with group, be seen favorably by others
	Misunderstanding the responsibilities and requirements of the position
	Attempting to gain prominence by taking advantage of the fact that others do not realize they lack certain qualifications
Difficulty accepting each other's roles, (ex: Why is he in that position? or How is she qualified to do that? or How is he more qualified than me?)	Lack of knowledge of qualifications of other individuals

allows professors to form teams based on professor input criteria and a survey of students [50]. Silva and Flavia also investigated different methods of organizing individuals into complementary teams [57]. MacMillan et al. present a tool called TIDE for building optimal teams of military personnel [49].

Table 2.2: Potential problems that may occur with ad-hoc team formation due to team leaders

Team Leader	
Problems	Possible Causes
Not assigning a position or task to a team member who is truly motivated to pursue it	Lack of awareness of the interests, goals, or desires of the team member(s)
Assigning a position or task to a team member with no interest in or motivation for that position or task	
Assigning unqualified team members to a task	Lack of awareness of team member skills, or abilities, perhaps from not taking sufficient time to or inability to,measure and consider options (as in a group meeting when a leader asks for volunteers)
Lopsided Trust: assigning tasks only to those whom the leader already knows and trusts	Being much more aware of the skill levels, interests, and desires of certain team members than of others (such as when they are from the leader's home organization or department)
	Only those who communicate most frequently or emphatically get their information heard and acknowledged by the leader

Fundamental Areas of a Personnel Profile

Of course, teams are composed of individuals. To aid our investigation, we needed a uniform method of measuring the characteristics of individuals. Research into what areas to measure and how to measure them led to work by Dyer et al. [39]. In their respected work on team building, they propose that individual team-member motivation, or commitment to the team's goals, and having the right social and technical skills, lay the foundation for a team's success. Leadership is also cited as a crucial component of a successful team. We add what perhaps Dyer et al. had taken as given - that logistical considerations, such as location should also be included when deciding who to put on a team. These areas are what we will refer to as the "fundamental areas". We attempted to measure each individual's:

- Motivation
- Technical Skill

- Social Skill
- Leadership Ability
- Logistical Considerations

These broad categories effectively encompass many important sub-areas. For example, how skilled a given candidate for a team is in Finite Element Analysis (FEA) would fall under the fundamental area of Technical Skill. How good a candidate's interpersonal communication skills are would fall under the fundamental area of Social Skill. Whether a person lives in Delaware or India and what his/her security clearance is would be Logistical Considerations. While there may be some slight overlap among these areas, in general they have proved very effective in delineating personnel.

It's worth noting that many other researchers have investigated similar areas and identified important characteristics of candidate team members. But, while the names they use may be different, the content is quite similar. For example, Lafasto and Larson surveyed thousands of team members and leaders in Fortune 1,000 companies including science and engineering firms [58]. They state their characterization of necessary attributes of an individual for successful teamwork as "working knowledge", or the "sufficient experience to do the job at hand well and having the necessary problem-solving ability," and "teamwork factors" such as a positive personal style, an action orientation, and supportiveness. It's easy to see how, despite occasional small overlap, these characteristics can be quickly mapped to the fundamental areas derived from Dyer's work.

There are many ways these fundamental areas could be measured, such as by Naikar et al.'s suggestions [59]:

- Asking an individual for self-rating in a given area
- Asking an individual's peers, managers, or subordinates for ratings in a given area
- Testing an individual using some form of pre-validated test
- Recording an individual's use of some sort of tool, such as a Computer Aided Design (CAD) program

- Registering information from outside sources, such as university degrees, training certifications, etc.

One method of testing individuals is the Purdue Visualization of Rotations Test (PSVT:R), originally developed by Guay [60]. Developed in the 1970's, it is a reputable test of spatial manipulation ability (an analog for "CAD Talent"). The test examines one's ability to mentally rotate geometric figures and determine their orientation. Scores on the test have been shown to highly correlate with success in learning and in using CAD software [61–63]. Use of a new, revised version of the PSVT:R is administered by Dr. So Yoon Yoon of Texas A&M, who has validated the test's psychometric properties [64]. An example of the type of problem found in the PSVT:R can be seen in Figure 5.2. The test, which has a strong reputation as a reliable instrument, has been shown to be an effective gauge for predicting student abilities in areas such as learning and using CAD software [61–63].

A similar project called the "Hyperion UAV: An International Collaboration" involved students from universities from around the world in designing and building a UAV [65]. Their research highlighted the importance of communication and common tools among the different students and universities involved, but did not focus on methods of team formation or measuring the level of success of different teams. Still, these researchers did highlight the need for more information to be available to those forming design teams than simply knowing the educational status of each student. They also explained the need for more information when organizing teams is even greater for virtual teams of students:

> "Students at the same official academic level at different universities may have different technical abilities and backgrounds and all need to be integrated in the skills profile of the global team. Development of teams based on team member skills is important in all team work, but at the international level the scrutiny whether these skills are met is much more difficult."

While many researchers have investigated methods for designing more effective, complementary teams [59, 66, 67], few have investigated how to best design geographically dispersed student engineering design teams. Researchers such as Suchan and Hayzak, state that the process of selecting team members for virtual teams is critical to team success [68]. They also state that being able to successfully identify whether or not candidates for virtual teams have traits such as sufficient levels of social skill, personal motivation, and leadership for such teams is a particular challenge for management.

Complementary Skills

Espinosa et al. examined software development teams and found that teams with a shared mental model of the work being done performed better than teams without a shared mental model [51]. Some related work by Moreland et al. and Liang et al. has been done regarding collocated team performance [13,69]. They discuss the importance of teams forming shared mental models of the team itself. In other words, they claim that an important correlation exists between how aware team members are of each other's various relevant skills and knowledge and the performance of the team. Faraj and Sproull's research further supports the claim that the better a team's shared mental model of teammate skills, the better the team's performance should be [70].

Woolley et al. argue the importance of complementary skills [53]. They present evidence that when teams have people with the right skills in the right positions on the team that less communication, rather than more, is actually desirable. Situations where extra communication is required to coordinate team actions, according to Di Penta and Macmillan, are defined as being laden with "communication overheads" [11,71]. Hepworth et al. performed experiments with dispersed teams using prototype MUCAD tools [72]. They showed that in addition to communication tools, multi-user organizational tools, such as a task list that any team member can view and edit simultaneously, can help to increase team performance for dispersed MUCAD teams.

Erickson and Gratton argue that how well teammates know each other may affect their team's performance. They state that the higher the percentage of strangers on the team and the greater the diversity of background and experience, the less likely team members are to collaborate effectively. A rule of thumb the authors offer is that at the very least, 20 percent of teammates on a new team should know each other [73]. Levi clarifies this point by explaining that what he terms "surface level diversity" (personal attributes such as age or race) and its related negative effects on team performance tend to dissipate over time. Meanwhile "deep level diversity" (functional attributes such as field of expertise) and its related positive effects on team performance tends to become more easily exploited over time [9]. Based on these sources then, it seems reasonable to assume that the more quickly virtual teammates can get know each other and build their shared mental models, the better.

Swaab et al. argue convincingly that the effects of having talented members of a team are more nuanced than a simple linear, positive relationship between level of talent and team performance [74]. They show that, even though most people assume that in general more talent on a team correlates with higher performance, in fact, for certain types of teams, more talent can correlate with a decrease in team performance. They show that different types of teams tend to respond differently to increasing levels of talent. For example, professional baseball teams see continued increases in performance with increased talent, while basketball teams see performance level off and even decrease after a certain point.

2.6 Literature Related to Minimizing Process Losses

2.6.1 Factors Affecting Virtual Design Team Performance

A major focus of this research is minimizing the effects of process losses, many of which are potentially more intense in virtual, geographically distributed, engineering design teams.

Communication Overheads

As mentioned earlier, Brooks studied software project teams and found that the amount of team productivity gained by adding a member to the team often begins to diminish as more and more team members are added [23]. The reason, the author explains, is that the tasks require teammates to communicate in order to coordinate their efforts to accomplish the task. Most technical tasks, they argue are not “perfectly partitionable” tasks, in which the amount of time to complete the entire project would be determined by 2.5.

$$t = \frac{1}{n} \tag{2.5}$$

where t is the time required for a team of n members to accomplish a given task. In this ideal case, as more members are added to the team, the work takes less time until it approaches zero.

A more realistic scenario, they argue, realizes that as more teammates are added, the time required to collaborate all their efforts also increases, creating a point at which adding more teammates nullifies any gains, and can even increase the overall time required for the project.

Hepworth et al. demonstrated a connection between communication overheads and effective MUCAD modeling [72]. Modeling teams using NXConnect to simultaneously contribute to the same model were able to finish their models more quickly when they exchanged fewer communications. See the next subsection for more details on Hepworth et al.'s work. Identifying the optimal number of teammates for a task, as discussed previously, is an important portion of research, but so is identifying methods by which communication overheads can be reduced, thus increasing the optimal size of a MU team. Stated another way, understanding what factors can help to move the the curve's optimal point outward can also help to maximize $Prod_a$.

Macmillan et al. also investigated the cost of communication overheads on teams, this time in teams of officers planning military missions [11,49]. They classify two types of coordination that occur in teams: implicit and explicit. Explicit coordination is coordination that involves sending and receiving messages in some form to articulate thoughts about actions, plans, and responsibilities. Implicit coordination does not require any overt communication, but is based on teammates sharing some predefined idea of the work they are trying to accomplish together.

Shared Mental Model of Work

Macmillan and others call this predefined, shared idea of the work the team is trying to accomplish a "shared mental model" [11,13,51]. This most commonly is a shared mental model of the work the team is trying to accomplish together. For example, a basketball team's shared mental model may be the play they are trying to execute on offense or the defense they'll set up. Each player thinks of the same mental model that would likely include the layout of the court, the ball, the hoop and backboard, as well as a common vocabulary that allows them to understand each other quickly and easily; "Let's run a pick and roll," or, " Let's set up a 3-2 zone."

Hepworth et al. demonstrated in a laboratory experiment that virtual, MUCAD teams using a tool meant to enhance the formation of a team's shared mental model (in their case, a to-do list that all team members could edit) communicated less overall, with the largest reduction in communication being communications to clarify points of confusion, especially about roles and responsibilities [72]. Teams using their tool also tended to complete their work more quickly than teams without the shared-mental-model enhancing tool. MacMillan's experience with military teams corroborates Hepworth et al.'s findings. Teams which can minimize the need for explicit communication improve team performance [49].

Espinosa et al. similarly describes how their research showed that having a shared mental model had a positive effect on teams that develop software by decreasing the needed development time [51]. Moreland et al. describe laboratory experiments in which teams who received group training performed a task more effectively than teams whose members received training individually. The supposition is that teams who were trained together developed not only an individual understanding of the task process, but also developed a shared mental model of how the process worked [13].

Shared Mental Model of Team

Moreland et al.'s research delves deeper into the idea of a shared mental model and explains that a shared mental model of the work being done by the team is a necessary condition but is not sufficient for exploiting a team's full potential for success. In addition to a shared mental model of the work that needs to be done, a team must have a complete shared mental model of the team itself, including the skills and knowledge of the team members [13, 69]. Returning to the basketball team analogy, in addition to the shared mental model of the court, hoop, and the play to be executed (the shared mental model of the work) the team would also benefit greatly by knowing what players on the team are best suited to be guards, forwards, or center, who shoots well under pressure, and or who has great ball-handling. Citing examples from coal mining safety to banking, and college students in a trivia competition, Moreland et al. assert that knowing who knows what and who is good at what is crucial for a team to reach its true potential.

Faraj and Sproull found that simply having team members who are experts in various important subjects on the team is not sufficient to produce high quality work, but that team member expertise must be coordinated [70]. Woolley et al. report similar findings [67]. This of course, requires teams to know who knows what. Their analysis showed that when teams do coordinate their activities based on thoroughly understanding which team members possessed which skills, team performance showed marked improvement, even over teams with similar levels of subject matter expertise. The challenge of coordinating team member expertise may be even greater on virtual teams, according to the researchers.

Teams must continue to refine this model of themselves and the work being done individually and collectively after each design project. According to Schippers and Stempfle, this can be accomplished by teams reflecting on their past performance [75, 76].

Team Trust

One reason virtual teams may face even more challenges than other teams is that an essential element of effective teamwork is trust. Trust between teammates, in turn is based in large part on familiarity with each other [52]. Kramer and Tyler explain that if team members are not able to familiarize themselves based on previous experience, they will import their expectations regarding a new teammate from other settings, quickly imposing categorical stereotypes.

Parker comments on the idea of "Swift Trust" for virtual teams as one possible way to mitigate low trust on virtual teams [16]. Swift Trust, or the quick determination by team members that their teammates are trustworthy and competent, occurs when team members assume all members of the team have been screened and are worthy to be members of the team. Establishing this type of trust can be very beneficial for teams whose opportunities or time to build relationships before beginning actual work are limited.

Leadership and Communication

Leadership is widely considered to be an important factor in team performance [77, 78]. Communication has also consistently appeared as an essential element for project success in engineering teams [65]. Several sources show that communication is most effective when it is used to form a common mental model among team members [11, 51]. According to Macmillan et al., large quantities of communication can be detrimental to team performance. However, when team members must develop a new mental model or modify an existing one, they need to be encouraged to speak up and express observations, questions, and concerns. This initial communication facilitates building shared experiences and gaining confidence in new technology or other changes. If the leader does not perform the role of promoting this productive communication, team performance will be negatively affected [79]. This is especially important in action teams, in which team members must work together in uncertain, fast-paced situations.

One of the great challenges of virtual collaboration is, of course, selecting which communication method to use. Various methods of communication to span distance and time have been developed and continue to be refined. Each of these mediums has its own characteristics and qualities. Maruping and Agarwal cite media synchronicity theory to emphasize that virtual collaboration effectiveness depends largely on using the correct communication medium for the task [80]. Levi agrees, stating that a communication tool's effectiveness depends on the fit between the requirements and the characteristics of the tool [9]. It follows that knowing and understanding the characteristics of the various types of tools available for collaboration are essential to effective team communication.

A given communication medium may have various qualities or characteristics by which it can be measured. Perhaps the most commonly cited characteristic in the literature, developed by Daft and Lengel, is "richness", or the ability to transmit a given amount of information in a given amount of time [81]. An example of a rich communication medium would be talking face to face with someone in the same room, while an example of a low-richness communication medium is a simple text message, such as those sent via mobile phones. In the case of the in-person conversation, multiple forms of communication, such as words, voice inflection, facial expressions, body-language, and context, are all transmitted and received simultaneously and with low effort on the part of the sender and receiver. Most of these are missing or are more difficult to transmit in the case of the text message.

Other researchers have offered other important characteristics of communication mediums. Maruping and Agarwal identify five: Immediacy of Feedback, Symbol Variety, Parallelism, Rehearsability, and Reprocessability [80]. Driskell et al. give six criteria: Co-presence, Visibility, Audibility, Cotemporality, Simultaneity, and Sequentiality [10]. French et al. suggest two: Synchronous, and Asynchronous communication mediums [33]. Maznevski and Chudoba describe mediums according to four characteristics: Accessibility, Richness, Social Presence, and Recipient Availability [82]. Levi And Rinzel identify five: Speed, Interactive, Richness, Social Presence, and Document Message [83].

The definitions of these characteristics given by these researchers overlap with each other in many areas. Comparing the definitions offered by these authors for each of their characteristics and considering our own experience, we suggest the following set of metrics by which we will judge communication options in this study:

- Media Richness
- Symbol Type
- Time to Response
- Durability / Permanence
- Parallelism
- Accessibility

Media Richness we define in the same way as Daft and Lengel which was described above. Symbol Type can be described as the classes of "symbols" used to transmit the message. For example, Dym et al argue that various languages are needed for design to successfully take place, such as verbal or textual statements, graphical representations, and mathematical or analytical models [84, 85]. We propose that in addition to the types suggested by Dym et al. that types such as audio, video, and body language, are also important. For example, a raised eyebrow during an in-person conversation may symbolize doubt or concern more succinctly than a textual statement in an instant messaging application. It may be tempting to assume that a richer communication medium is always desirable, however, as pointed out by Levi, in certain situations, such as group brainstorming, too rich of a medium has actually been shown to hinder group effectiveness [9].

The types of symbols available in a medium can influence how effective it is at communicating certain types of messages. For instance, the emotion stirred by a heart-felt phone conversation (audio symbol type) may be difficult to transmit if the same conversation were attempted via a shared-spreadsheet application such as Google Sheets (mathematical model symbol type). Meanwhile, a quick, hand-sketched map with arrows indicating the route to follow (a graphical symbol type) could be more useful than a 10 minute phone conversation (audio symbol type) to ask for directions. Symbol type can make a big difference.

Time to Response refers to two closely related characteristics: the ability of the medium to enable a response to a message in a certain amount of time (instantaneously or slower), and the socially dictated time within which a response is acceptable. These two sub-characteristics we call "response enablement" and "social acceptability". As an example of response enablement, it takes time to type a response to an email, click send, and then possibly wait for network latency. Depending on context, however, it can often be socially acceptable to not respond to an email for as long a couple days. In the case of a face to face conversation, however, messages are sent and received without delay and a pause of more than a matter of seconds could be a social miscue. In fact, one could argue that in face to face conversation, one can never really stop communicating, since even if one ceases to speak, visual cues continue to be transmitted.

Durability/Permanence explains how easily the contents and sequence of an exchange are recorded and reprocessed. While the contents of an email and its subsequent replies are automatically preserved in order without any extra effort by the communicators, the same is not true of many other mediums, such as when making a telephone call or having a face-to-face conversation. Special solutions or tools to record various types of communication may exist, but for this definition we consider only those tools which, as a normal, built-in characteristic, include automatic recording and ordering of messages as a standard feature for all users.

Parallelism describes whether a communication medium allows the user to carry on multiple conversations simultaneously. For example, when speaking with someone in person, one is unlikely, based on social acceptability and convenience, to try to carry on more than one conversation at a time. However, when using a cellular phone to send text messages, it is common to be involved in conversations with multiple different individuals nearly simultaneously, texting each in turn.

Accessibility addresses the fact that some communication tools require either special skills or special tools to use them effectively. For example, to successfully video conference over the internet, all participants must have special tools, including the software of the tool being used. They must also all have the necessary hardware, such as a webcam, and the knowledge to use the software and hardware tools. As many people who have attempted to video conference with a large and/or diverse group know, the result of any member of the group lacking any one of those tools or skills results in incomplete or hampered communication. Another important aspect of Accessibility is access to resources such as high-speed networks and permissions, including firewall access. Access is also important in other, less technical mediums of communication, such as speaking in person. While requiring no tools or special knowledge beyond the ability to fluently speak a given language, geographic proximity is at least as limiting to using this medium as access to a high-speed internet connection is to web-conferencing. Having to travel significant distances to communicate face to face definitely affects the accessibility of this medium in today's engineering environment.

Considering each of these characteristics, a much clearer comparison can be drawn among the various communication mediums available to teams such as those that participate in the AerosPACE program. We adapt the lists of communication tools from French et al., Maruping and Agarwal, Lengel and Daft, Driskell et al., and Levi for our use:

- Face to Face
- Telephone (one to one)
- Teleconference (many to many)
- Voice Mail
- Text / Instant Messaging
- Web Conferencing
- Video Conferencing
- Email
- Wiki
- Shared Visual Editing
- Shared Data Editing
- Forum / Discussion Thread (including social networks)

A comparison of these tools based on the criteria described above can be seen in Table 2.3. Although most of these communication and collaboration tools are well known and easily distinguishable, some of them deserve slightly more description in order to avoid uncertainty regarding what they are. Teleconferencing, Web Conferencing, and Video Conferencing are all similar in some ways, but distinct in others. In this paper, we define Teleconferencing as a group communication method that is essentially a telephone call for more than two people. The call can be made using traditional land-line or cellular telephones, or over the internet, provided that voice (audio) is the only symbol type used. Web Conferencing could include services similar to Teleconferencing, but also includes internet based tools that allow participants to share screens, view slides, or similar features in addition to hearing each other's voices. Thus Web Conferencing uses more symbol types than Teleconferencing. Finally, Video Conferencing tools, such as Skype, include all the previously mentioned capabilities as well as the ability to see a live video feed of each participant.

It is worth noting that, in our experience, especially in the example of these three tools, the level of Symbol Type variety included in one tool and the Accessibility of the tool have a generally inverse relationship. A Teleconference is usually relatively simple to set up, the hardware (a telephone) is simple, knowledge of how to use the hardware and software is common, and land-line or cellular telephones are nearly universally available. Web conferencing, while increasing Symbol Type variety, also decreases its Accessibility by increasing the requirements for its use: a computer with access to a sufficiently fast internet connection is needed, to use the audio communication symbol type requires either the computer to have a working microphone and speakers, or access to a teleconferencing service that is integrated with the web-service. A knowledge of how to use the software and hardware is also required. These requirements all serve to decrease the Accessibility of the Web Conferencing tool. Video Conferencing adds the need for a web-cam and knowledge of how to use it on top of the requirements for Web Conferencing. A significantly faster internet connection is also necessary for a successful Video Conference. While improving networks and computer tools may be increasing the Accessibility of these tools, our experience has shown that these barriers are still significant and should not be ignored.

Table 2.3: Different communication tools and mediums compared using various characteristics and metrics.

	Media Richness	Symbol Type	Response Time		Durability	Parallelism	Accessibility
			Response Enablement	Social Acceptability			
Measurement	Low, Medium, High	Text, Audio, Visual, etc.	Seconds, Minutes, Hours, Days, Longer		Low, Medium, or High	Only One, Two, Multiple	Low, Medium, High
Face to Face (F2F)	Highest	Multiple	Seconds	Seconds	Low	Only One	Low or High (depending on location)
Phone Call (1 to 1)	Medium	Audio	Seconds	Seconds	Low	Only One	High
Teleconference (x to x)	Medium	Audio	Seconds	Seconds	Low	Up to Two	Medium
Voice Mail	Medium	Audio	Minutes	Days	Medium / High	Only One	High
Text / Instant messaging	Low	Text	Seconds	Minutes or Hours	High	Multiple	High
Web Conferences	Medium-High	Multiple (though fewer than F2F or Video Conf.)	Seconds	Seconds	Low	Up to Two	Medium
Video Conferencing	High	Multiple (though fewer than F2F)	Seconds	Seconds	Low	Only One	Medium-Low
Email	Low	Text (although other can be attached)	Minutes	Hours or Days	High	Multiple	High
Wikis	Low	Text (although other can be embedded)	Minutes	Weeks or Years	High	Multiple	Low
Shared Virtual Annotation and Drawing Tools	Medium	Sketching or shape manipulation (may be combined with audio or text)	Seconds	Seconds	Medium	up to Two	Medium
Shared Data Editing (GoogleDocs, ShareLatex)	Medium	Text	Seconds	Minutes to days	High	Up to Two	Medium
Forum / Social Networks	Low-Medium	Text, static images	Minutes	Days or Longer	High	Multiple	Medium

2.6.2 Need for Novel Multi-User Tools

While many of the communication and collaboration tools listed above are well-developed, commonly used, and have proven effective in many situations in the design process, there remain situations that are important for enabling effective work in a virtual, MUCAx engineering design team setting for which effective tools have *not* yet been developed or tested. These are areas where potentially great improvement can be made in the work done by these teams. Hepworth et al. provide a recent example of such a tool and its potential [72]. The researchers developed a MU tool to use in conjunction with MUCAD tools (although it could easily be implemented as a standalone tool or integrated with other MUCAx tools) that enabled users to create a much clearer shared mental model of the work to be accomplished. Results of their experiments showed significant improvements in the time required to complete modeling tasks when working as members of virtual MUCAD teams.

Only a handful of other tools have attempted to provide this kind of real-time, multi-user ability in the product development process. Research tools, such as NXConnect [1, 7, 34] have demonstrated the ability to enhance existing CAD software tools (in this case, Siemens NX) to provide a real-time, multi-user environment. Onshape has developed a commercial, cloud-based CAD tool with a level of sophistication similar to Solidworks and the ability to collaborate in real-time with multiple users [8, 86]. While tools such as these provide a needed and major step toward enabling true virtual engineering design teamwork in many stages of the product development process, not all design work is done in CAD [87, 88]. There are portions of design process which necessitate different types of tools to improve collaboration in a virtual team environment.

Design is considered an essential, if not the integral skill, of engineers [84]. Sketching, as a “language of design” is an integral part of the design process, as noted by Dym [85] and others [89]. Do et al. argue that creating diagrams and drawings as part of the design process assists in generating concepts, visualizing problems, organizing thoughts, facilitating problem solving and creativity, and refining ideas [90]. Others have found that sketching aids in analysis of design quality in identifying errors, and improving overall design quality [88]. Some researchers have even found evidence to suggest a strong relationship between generating novel designs and including sketching as an essential part of the design process [91].

As noted by Ullman et al., one function of sketching, beyond recording an idea outside the designer's mind, is to communicate concepts to teammates [89]. Sachse et al. cite various sources to emphasize the importance of sketching as a communication tool for design team members [88]. A lack of currently available digital sketching tools and their potential for assisting in concept development in the early stages of design was also noted by Sachse et al. Bellamy et al. also note that even in our digital age, designers still tend to reach for pencil and paper or a whiteboard and marker during preliminary design [92]. Taken together, these points indicate that current virtual engineering design teams work under the burden of not having the same concept communication abilities as their collocated peers with regards to sketching.

For example, in one study of distributed engineering student design teams working from Texas and Qatar, distributed teammates sketched their ideas on paper, then scanned the ideas to exchange via email, adding a communication overhead that collocated teams do not have [93]. As will be explained later, this type of situation is similar to our own observations of geographically distributed engineering design teams.

Bentley et al. argue that, in order to support and encourage collaboration, virtual collaboration tools must make users aware of the actions of the other users, ideally in real-time [94]. Katz and Te'eni also emphasize the importance of what they term "contextualization" in improving collaborative performance for virtual teams [5]. Engineering educators, as well, have begun to recognize the importance of multi-site engineering design collaboration and have called for changes to curriculum to equip graduates to collaborate and communicate effectively as members of global engineering teams [19]. It follows that if students are to learn how to work in a global setting, the tools they use should support that kind of work.

Some virtual collaborative sketching tools have been developed, such as skWiki [95]. SkWiki, which runs in a web-browser, allows multiple users to use hand-held computing devices to sketch, first, on their own. Then, after committing, other users can choose to merge their own sketches with the committed sketches of others. Users of the tool stated that while there many aspects they appreciated, real-time updates is one feature they desired to be added. Research subjects felt a shared whiteboard would improve virtual collaboration.

An earlier tool, TEAMSTORM, provides access to multiple private and shared sketching canvases [96]. Designed for collocated use, teammates interacted via personal tablet devices as well as on a large, vertically mounted display screen. To edit other users' sketches, users can pass sketches back and forth via the shared virtual space provided, but editing of sketches simultaneously is discouraged by the system. GAMBIT, another tool, similarly allows users to share sketches to a large display [97].

Sketching on its own, as an idea communication tool, however, is not enough, according to some researchers. Jonson found, in his study of design ideation, that words were involved in the majority of what he termed the aha! moments the designers in his study experienced [98]. He suggests that a combination of verbal and visualization tools is more ideal than either alone. French et al., in a study of various engineering corporations, found that textual and verbal communication (i.e. emails and phone calls) were the most common communication methods for virtual engineering team [33]. In a later study, French et al. suggest that integrating visual and audio communication tools may be advantageous for virtual teams of designers [42].

Few studies have examined in any detail the effect a digital sketching tool, similar to the ones described, has on geographically distributed engineering design teams and their ability to collaborate. Chandrasegaran et al. studied a small sample (four participants) for their study. Users stated that, bugs related to the beta status of the tool aside, they felt the tool was effective, especially with allowing them to work from different locations. Few, if any other studies could be identified where users were asked to evaluate a digital sketching tool meant for virtual design teams. In the early 2000's, Lang et al. called for distributed design teams to have access to communication tools such as electronic whiteboards, which are similar in size and appearance to traditional whiteboards, but embedded with technology which allow users at different sites to see changes made to them [99]. They suggest that shared design workspaces with shared tools can enhance team morale and enrich distributed team communication.

Experiential Inspiration for a Shared Virtual Sketch Tool

The inspiration for a shared virtual sketch tool began while observing members of a multi-university capstone student design team attempting to work on the design of a small-scale model of a Boeing 777 for wind-tunnel testing. Students at Brigham Young University (Utah, U.S.A.) and the Georgia Institute of Technology (Georgia, U.S.A.) were discussing the shape and location of mounts for the model over an audio connection, but were experiencing difficulty understanding each other's ideas. To work around this, one student would take a screen-shot of the CAD model, open the image in MS Paint, annotate and mark the image, save it, attach the annotated screenshot to an email, wait for the other student(s) to open the attachment, and then discus the ideas represented. To respond, the students who had received the image would repeat the process. Example images from this experience can be seen in Figure 2.7, images A and B.

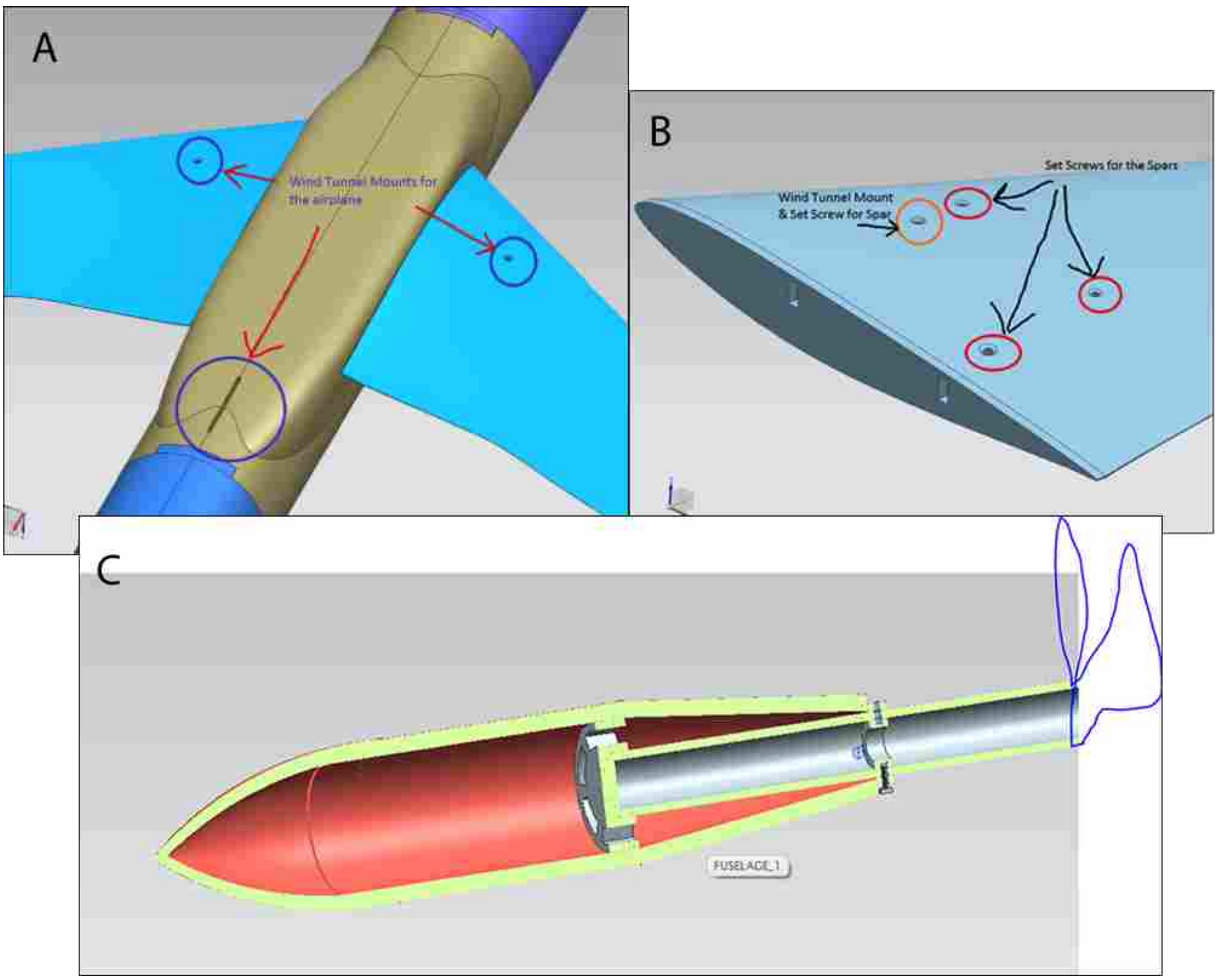


Figure 2.7: Screenshots of student CAD models which were annotated in MS Paint, then attached to emails or uploaded to shared wiki-pages in order to collaborate with remote teammates. Images A and B show a scale-model of a 777 and its modified wing where teammates were discussing wind-tunnel mounting options. Image C shows a cutaway view of the fuselage of a UAV and the roughly sketched idea for a V-tail.

In a following year, students in another Boeing sponsored capstone program demonstrated a similar need for quick, low-resolution annotation and sketching while determining what type of tail their unmanned aerial vehicle (UAV) should use. Students were working together from various universities across the U.S.A. and needed to communicate ideas regarding the design of the tail. One student posted an image of a sketched-on screen shot to the team's wiki-page where others could comment on it (see Figure 2.7 image C). Teammates joked with each other about the low-fidelity of the sketch, but a Boeing adviser commented,

> "What is funny is how good it is that you scribble it down before you spend time making it. Get some basic buy in before you waste time and resources on something that may not be going in the right direction."

In an interview, another student from the same program who had attempted to work with teammates at various universities across the U.S. to design, build, and fly their UAV even specifically stated, unsolicited, his wish for a tool that would facilitate this kind of communication. He and his team had resorted to using pencil and paper to sketch their ideas and then scanning them to email to each other, similar to the students in Texas and Qatar from the study described earlier. He describes the dilemma he and his teammates found themselves in when trying to choose the best tool to communicate their visual ideas to each other:

> "It's a little difficult, because, you know, if I want to draw something out, I don't want to sit and sketch it in CAD. It'd be easier if we were just in one room and I could draw it on like a whiteboard, you know it just takes more effort to communicate something simple that would take two seconds to do in person..."

This student's wish for the simplicity and ease of use of a virtual whiteboard echoes the response, mentioned earlier, of the users of the skWiki system [95]. Such tools do exist [100], but since they are web-based, the stringent IT policies of many large corporations restrict their use in many situations. In the absence of digital tools, students employ workarounds, e.g., using Webex and MS Paint to allow one user to draw while others watch and comment.

IBM researchers Bellamy et al. emphasize that digital tools for sketching can only be successful when they do not distract from the central experience of sketching [92]. Based on this principle, the literature reviewed, and our observations of virtual engineering design teams attempting to collaborate, we propose characteristics for a digital design sketching tool that can be applied synchronously:

- Simple and intuitive to use
  - Natural user interface
  - No need for specialized hardware
- Real-time visualization of the actions of other users, including cursor position
- Basic sketching and annotation tools
- Facilitation of image and screen-capture use
- Ability to mimic basic in-person collaborative gestures and motions without high software or hardware overhead costs
- Integrated audio communication

2.7 Conclusion

It is clear from these sources that in order to be successful, virtual teams of design engineers must overcome barriers to communication and collaboration that collocated teams working in a more traditional, collocated setting do not have to deal with. Although they face new challenges, these team members may also have greater opportunities than their predecessors, such as the ability with the correct types of tools, to integrate early stage sketching and ideation processes into the digital design process.

CHAPTER 3. DISSERTATION OBJECTIVE

3.1 Dissertation Objective

Based on the literature reviewed, the objective of this dissertation is to develop principles and methods to maximize virtual engineering design teams' potential productivity, minimize their process losses, and thus enable these teams to maximize their actual productivity.

3.2 Dissertation Organization

A useful analogy to understand the objectives of this research compares the work done by teams to energy and work in physics. In a classic example, a mass on a pulley gains potential energy by increasing the height between the mass and the surface of the earth. That potential energy can then be translated into either another form such as kinetic energy or into useful work when the mass is released. However, translating the potential energy of the mass to its next desired state is never 100 percent efficient, since air resistance, friction, and other sources of entropy siphon off some of the energy. In order to increase the amount of useful work obtained, one or both of two strategies may be attempted: 1) potential energy can be increased, 2) entropic losses can be minimized to improve the efficiency of the conversion process. So, an engineer might build a tower to increase the height to which the mass can be raised, or the engineer could install better bearings on the pulley to minimize friction, or create an aerodynamic shroud for the mass.

The organization of this dissertation will follow a similar pattern, but for virtual MUCAx teams: Chapters 4 and 5 will cover development of principles and methods of maximizing potential productivity (analogous to increasing the potential energy of the mass such as by increasing its height). Chapters 6 and 7 will treat development of principles and methods of minimizing process losses (analogous to decreasing entropic losses). Chapter 8 will bring together the conclusions on

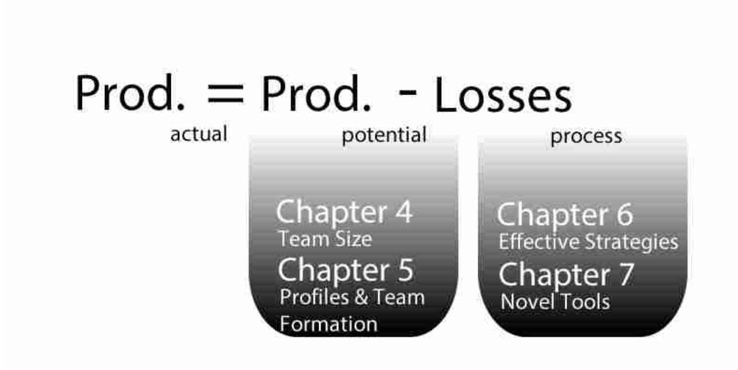


Figure 3.1: Chapters addressing different portions of the Steiner equation

the general topic, discuss limitations of the work, and suggest areas of future research. See Figure 3.1.

3.3 Research Methodology

Virtual MUCAx teams inherently involve the interfacing of humans and technology. Given the social and technical nature of the research, a mixed methods approach, or an approach using both quantitative and qualitative strategies, similar to that described by Borrego et al. [101], was deemed most appropriate. References to case-study style examples of findings as well as statistical analyses of quantitative data are presented to validate hypotheses and other findings.

3.4 Notes

While much of the research described in this work was conducted with undergraduate students studying engineering or related topics, it is generally assumed that the findings are applicable to engineering industry as well as engineering students.

CHAPTER 4. MAXIMIZING MU PERFORMANCE BY OPTIMIZING THE NUMBER OF TEAMMATES

4.1 Introduction

While past research gives indications that there is an optimal number of simultaneous contributors for a given CAD part, no one has made any attempt to determine what factors influence this number. Furthermore, no one has yet determined any method to adequately predict this optimal number. In this chapter, we present factors related to the part itself that appear to influence the optimal number of simultaneous contributors in a CAD part. We also present two methods to determine or predict this value. These methods use a taxonomy, as well as a dependency tree structure, to classify the part and, in turn, estimate the optimal number of users. We then present results of experiments to determine empirically which of the two methods most accurately predicts the optimal number of multi-user team members.

4.2 Taxonomy

A taxonomy is a structured way of grouping or distinguishing a large and diverse set of specimens, which is useful in many fields such as biology [102], astrophysics [103], or even systems engineering [104]. For example, biological taxonomy, with its kingdom, phylum, class, order, family, genus, and species, allows us to classify living things in a neatly structured fashion. Todd et al. provide a similar method of classification for manufacturing processes, beginning with whether a process is shaping or non-shaping, and progressing all the way down to specific processes such as Ion Beam Cutting and Swaging [105]. These taxonomies serve significant practical purposes beyond simply organizing objects. It is easy to see that much of biological research would be impossible without a standardized way of understanding how different species are related. Similarly, an organized way of thinking about manufacturing processes allows designers and manufacturers to systematically consider alternatives for making planned products a reality.

In order to identify the optimal number of MU teammates for a given part, a structured method of classification must be established. Just as living creatures and manufacturing methods can be classified and organized using a taxonomy, models of physical parts that are created in CAD can also be organized using a similar scheme. An image illustrating our proposed taxonomic method is presented in Figure 4.1. Starting at the top with “All Parts,” the first level of distinction includes determining whether the part has a single feature or multiple features. A feature, in this research, is defined as any of the geometry-creating methods in a modern CAD tool such as Siemens NX or Dassault CATIA. Examples include “Extrude” in NX or “Pad” in CATIA, “hole”, “pattern”, or “loft” features. Sketches, by themselves, are not considered features in this method.

If a part only has a single feature, it is considered unsuitable for MUCAD. This is because the feature is the atomic unit, meaning only one user can edit a feature at a time [106]. If, at some future period, a MUCAD system alters that paradigm and adds capability for MU sketching, this taxonomy would change (see “Sketch Domain” on the far left of Figure 4.1.). The other option at this classification level is for a part to have multiple features.

Level two of the taxonomy requires identification of whether the part has linear or branching dependencies. Dependencies occur when one feature in a part depends on another feature in some way. For example, a hole may depend on a surface or a solid on which it is based. If multiple features depend on a single parent feature, these children are said to branch. An example of a part with purely linear dependencies is shown in Figure 4.2. The features in this part must be completed in the shown order and no features can be completed concurrently. That is, each feature has only one antecedent feature and one descendent feature. In contrast, Figure 4.3 and Figure 4.4 respectively show a piston head and an automotive fluid reservoir with their feature dependency trees. In these parts, a given feature may have multiple features upon which it depends or which depend on it. The automotive fluid reservoir tree demonstrates a relatively high amount of branching dependencies.

A final example demonstrates the level of complexity parts can reach. Figure 4.5 shows a stamped sheet metal automobile door and its feature dependency tree. As can be seen, the features branch quite widely. Although because of resource constraints parts of this size were not included in the testing performed, it represents an excellent opportunity for future researchers to examine.

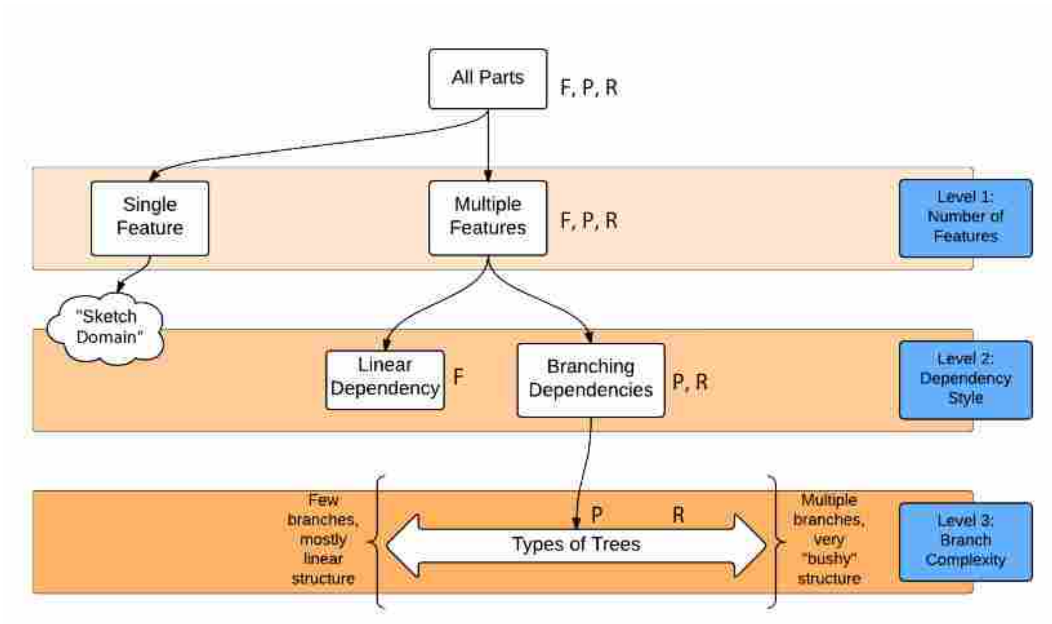


Figure 4.1: Basic taxonomical structure. Item F represents the fan blade, P represents the piston head, and R represents the automobile fluid reservoir

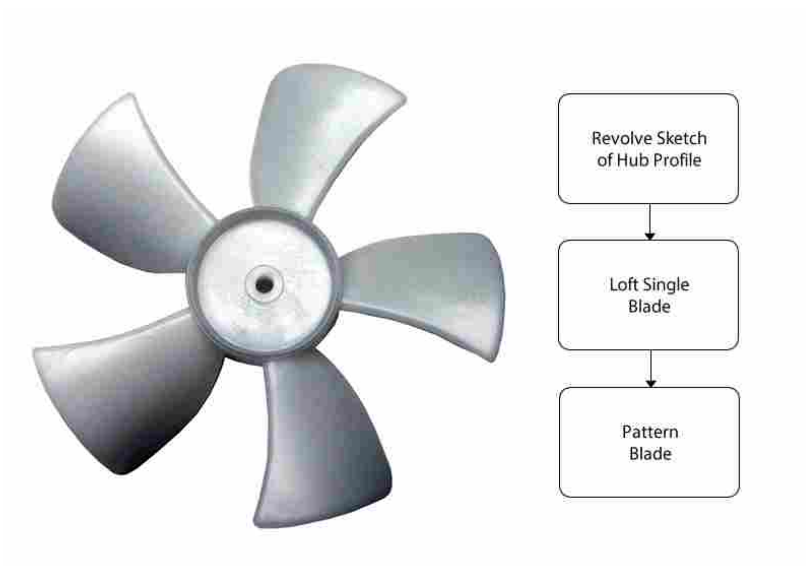


Figure 4.2: An example of a part with purely linear dependencies

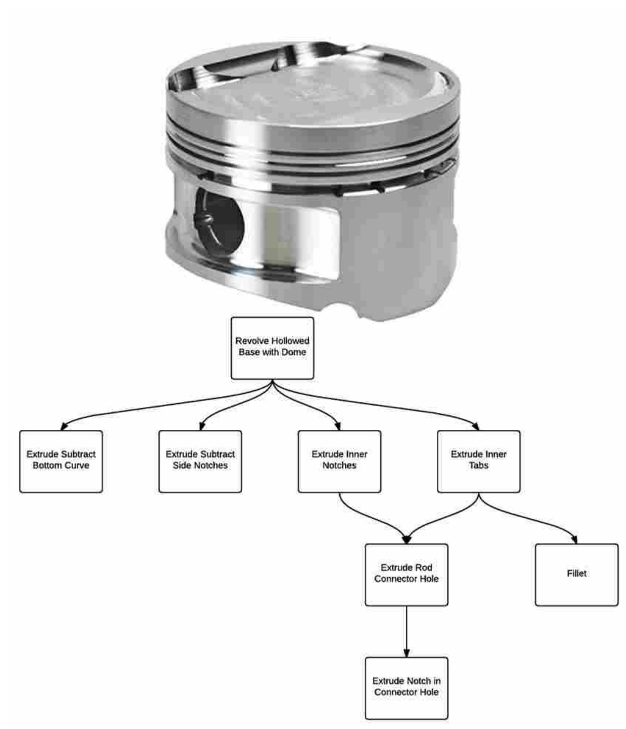


Figure 4.3: The features of this piston head demonstrate branching dependency

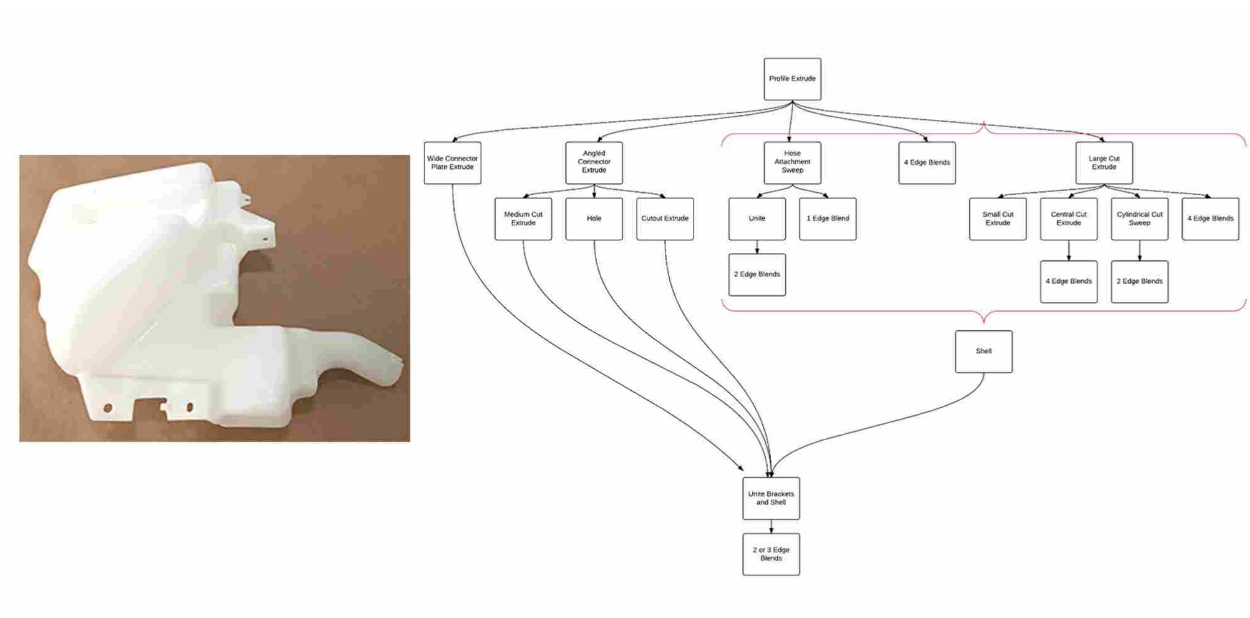


Figure 4.4: This automobile fluid reservoir demonstrates a part whose features branch significantly

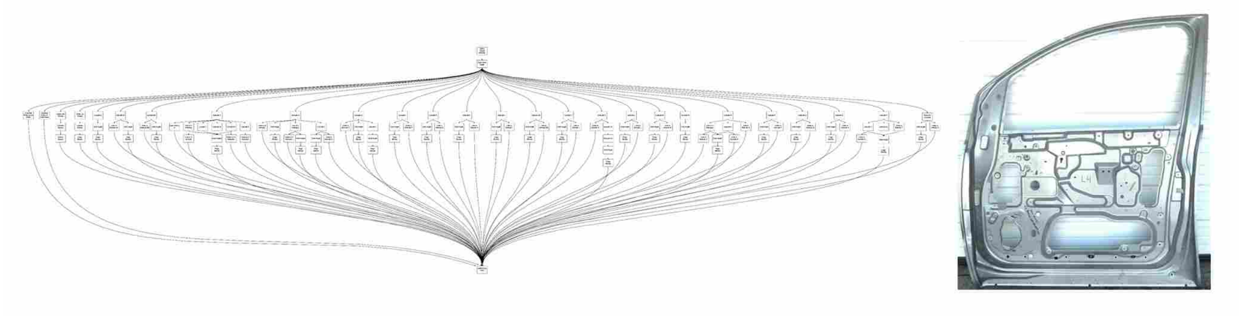


Figure 4.5: Feature dependency tree for a stamped sheet metal automobile door

A visual representation of a part's dependencies often bears resemblance to the structure of a tree. How complex the tree structure of any given part is, from mostly linear at one extreme to complex and bushy at the other extreme, is the third and final level of our taxonomy.

Using this method, which is, as far as we are aware, unique in the field, we have classified a sample of more than 100 parts. To ensure a minimal breadth of part variety, we selected parts from among nine different manufacturing methods, such as blow molding, sheet metal manufacturing, forging, and 3D printing. Next, a researcher classified each part using the taxonomy (aided by standardized classification forms) and, as applicable, created the feature dependency tree for each part. A second and sometimes third researcher verified the classification and tree structure to confirm the part's taxonomic definition. This collective set of classifications could then be used to develop predictive models to estimate the optimal number of users for a given CAD part.

Currently, CAD part classification is a manual process requiring researchers to think extensively about how they would model a part and then check each other's proposed structure. In the future, an automated tool leveraging machine learning could conceivably be developed to automate this process. However, such a tool would be required to handle the ambiguity of multiple options for how to model a given piece of geometry which imitates a human modeler.

4.3 Predictive Models

To accurately predict the optimal number of users for a given CAD part, an overall methodology and a set of predictive models were proposed for investigation. Since this research was the first step in filling an apparent gap in MUCAD implementation, a classic pattern of increasing fidelity from simple to more complex models of prediction was followed. This is not unlike various methods for aircraft design and aerodynamics where lower order models are initially applied to obtain first order approximations, followed by more accurate and sophisticated methods [107].

For example, during conceptual design, an aircraft designer may simply apply Bernoulli's incompressible flow equations to extract simple estimates of drag polars from a point design. During preliminary and detailed design, one may invoke Euler's and Navier-Stokes equations, which can include compressibility and viscosity, respectively, resulting in more accurate predictions of the aircraft's various aerodynamic performance metrics. Finally, aircraft models are tested in wind tunnels, validating the models' predictive capability for a particular geometry.

In the context of MUCAD, the lowest order model proposed predicted that the optimal number of multi-users working concurrently in a CAD part would simply be a function of the number of features within that part. According to this model, a part from the sample of parts classified using the taxonomy previously described could be selected, the number of features quickly calculated, and the optimal number of users can then be extracted from a linear regression model. Under this model, we hypothesized that for parts with few features (i.e. less than 10) no significant benefits would be obtained from more than one concurrent user. Therefore, a single user would be optimal. The additional overhead of MU environments and the necessary communication requirements may outweigh the benefits with so few features in a part. However, we hypothesized that with more features (i.e. more than 10), the potential for multiple users working simultaneously in the same CAD part will become increasingly attractive. When these parts are modeled by multiple users, the team can experience a reduction in overall modeling time, reduced or accelerated error checking, and enable earlier efforts by analysts and subject matter experts down-stream.

A more sophisticated, second order model takes into consideration not just the number of features but the features' location and orientation with respect to the feature dependency tree. This model predicts that a tree with little to no branching, even with many features, will not allow multiple users to concurrently model a part. On the other hand, a part with significant branching suggests potential for many simultaneous users. This model uses the feature dependency trees generated during the taxonomic classification to count the number of features within a particular tier or level of each tree's hierarchy. Then, a weighted sum across all branches and levels is performed to predict an optimal number of multiple users. We hypothesized that this model will more accurately predict the optimal number of users for a given part than the first order model.

A third and more complex model would make fewer assumptions about the feature dependency tree and would consider the time and or complexity associated with modeling each feature with an evaluation of the interfaces between them. Additional factors could be included in this model that can drive the optimal number of users, including ideas from graph theory such as connectivity, path lengths, and cycles [108]. Since this third type of model requires information beyond what was gathered in the taxonomic classification of the part sample described, it forms the thrust of future research efforts whereas this paper will address the first two models described. Finally, efforts to validate these models was performed through 60 design tests with teams of different numbers of users.

4.4 Model Validations - Experimental Method

The first and second models were investigated empirically by measuring the time required to model 13 "small" parts (20 or fewer features) and two "larger" parts (more than 20 features). Each part was modeled with one, two, three, and four MU team members. Users were never allowed to model the same part twice to control for learning and reduce the bias in observed quality and modeling time. Because of the number of models that had to be created, 26 volunteers from the Brigham Young University (BYU) CAD Lab and other student-volunteers with significant NX CAD experience modeled the parts. Students were mostly undergraduate mechanical engineering majors.

In order to calibrate and compensate for the large variety of modeling skill levels, each user took a modeling speed test. This test, completed individually by each volunteer, required the examinee to model a basic part. Trained proctors verified satisfactory completion of the part and recorded the amount of time required. Equation 4.1 shows how a correction factor is calculated to normalize the individual skill level for all participants:

$$R_c = \frac{t_{avg.}}{t_{user}} \tag{4.1}$$

where R_c is the compensation ration, $t_{avg.}$ is the average time from all users' speed tests, and t_{user} represents an individual user's speed test time.

Another potentially confounding factor which we attempted to mitigate is the beta status of the NXConnect MU software. Software bugs did occasionally cause individuals to spend time waiting or restarting the program. To compensate for this, video recording of each user's screen was examined after each model was completed and the time a user spent waiting due to bugs was subtracted from his/her total modeling time to produce the active modeling time for each user. Each user's active modeling time was then summed with the other members of his/her team and averaged to produce the corrected calendar time for each modeling effort described in Equation 4.2.

$$T_C = \frac{R_{c,min} \Sigma_1^k (t_{modeling} - t_{bugs})}{k} \quad (4.2)$$

where T_C is the corrected calendar time for each model, k represents the total number of users on the team, $t_{modeling}$ is the raw modeling time for each user, and t_{bugs} represents the time a given user spent waiting because of software bugs.

Steiner, Page, and Moynihan state that the performance of teams whose members are highly interdependent (those performing "conjunctive" tasks) depends most on the team's "weakest link" member, or the team member with the lowest rating in the relevant skill [20, 109, 110]. In the case of the MUCAD teams in this study, R_c was used to indicate team member skill. In other words, the lowest R_c, or the $R_{c,min}$ was applied to weight each team's T_C. This assumption was supported based on the observations of MUCAD teams, which demanded high levels of interdependence: they must agree on how to orient the part, decide who will model which sections, and depend on each other's sketches and features to create their own.

4.5 Results

Results of the part modeling experiments can be seen in Table 4.1, arranged in order from smallest number of features per part to the highest. Some parts varied significantly from the expected overall trends, but many matched well.

Table 4.1: Completion time results for the part modeling experiments, organized by increasing number of features

Part Name	Total # of Features	Avg. # of Features / Row	Tc 1-User (min.)	Tc 2-User (min.)	Tc 3-User (min.)	Tc 4-User (min.)
Sintered Part	3	1.5	9.89	8.29	6.58	9.03
Cup	4	1	1.82	3.54	11.12	5.80
Ball Valve	4	1.33	2.20	6.07	3.43	2.51
3D Printed Hinge	7	1.75	8.83	16.91	11.95	7.93
Tablet Mount Arm	7	2.33	34.76	18.02	13.36	8.40
Chocolate Container	9	2.25	27.49	39.78	12.07	12.34
Mining Machinery	10	1.43	28.91	16.93	13.75	17.91
QuadCopter Arm	10	2.5	35.71	37.44	20.17	12.94
Fan Housing	13	6.5	27.17	22.16	12.91	13.56
Kitchen Sink	15	3	64.59	12.97	25.27	19.44
Car Door Panel	17	2.83	39.59	32.17	20.87	18.47
Gear Pump Housing	17	4.25	40.53	35.96	26.95	23.98
Pump Casing	19	3.16	30.38	16.55	21.37	22.71
Airplane Rib*	32	10.67	18.59	28.62	26.01	24.03
Tray*	59	5.9	25.08	27.03	25.28	31.93

**included as case-studies*

Comparing the TC of the 13 small parts to the number of users per team, one can observe a trend similar to what was found by Hepworth et al. and Brooks [23,48]. Figure 4.6 shows the time to complete each part compared with the number of users on each team as well as a line connecting the mean time in each category with 95 percent confidence intervals. As can be observed, between one and two team members, the time to completion improves noticeably. Between two and three team members, the time to completion improves again, but not by as much as between one and two. Finally, between three and four team members, more improvement is achieved, but is very small.

Given the data's non-normality and potential for inequality of variances, a non-parametric, Wilcoxon each pair comparison was used to compare the means of each group. Mean values were: 1 User: 27.1 minutes, 2 Users: 20.5 minutes, 3 Users: 15.3 minutes, and 4 Users: 13.5 minutes. The difference between the 4-User teams and the 1-User teams was statistically significant ($p = 0.04$). The next closest difference to statistical significance was the difference between the 3-User and the 1-User teams ($p = 0.06$).

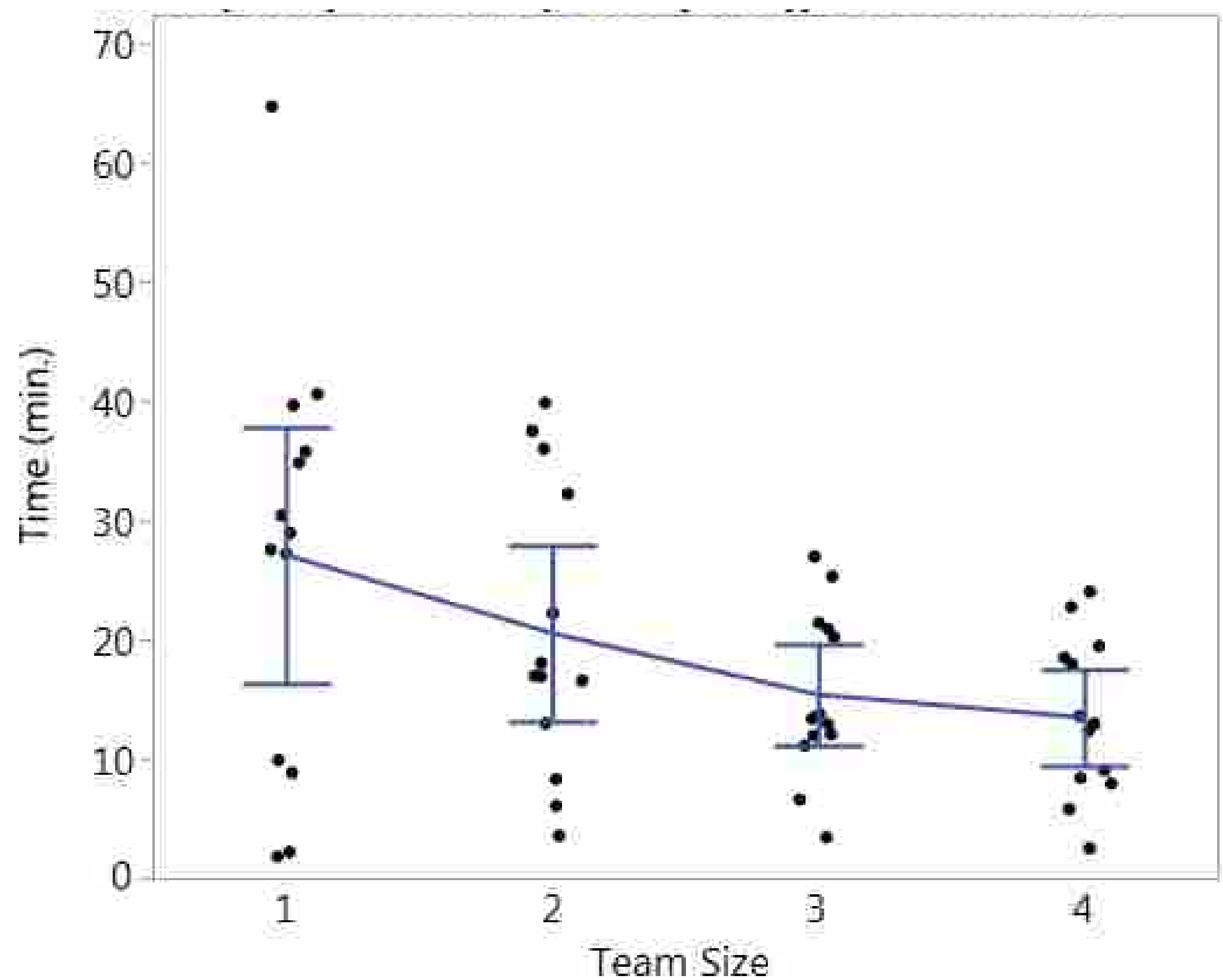


Figure 4.6: As the number of teammates increases, the average amount of time to complete a model decreases, but the improvement or reduction in time begins to levels off by four teammates.

The optimal number of MUCAD teammates was determined for each part by identifying the point at which adding more users no longer saved time, or, in the case that the classic Brooks pattern was not displayed, the number of users correlated with the shortest time to completion. A first-order linear regressed model of the optimal number of teammates was determined from the number of features per part and the average number of features per row within the part's feature dependency tree. These curves are shown in black on both the left and right hand side of Figure 4.7. The linear relationships do demonstrate a positive correlation, as expected, but both are quite weak statistically with a small R^2 value of just 0.065 when the model is based on the number of features, while the model for the average number of features per row was only slightly better at 0.076.

However, since the true model would be constrained to have "1" as the optimal number of users when the total number of features equals one, and the model should asymptotically approach a maximum number of users for practical reasons, (i.e. the overhead of integrating a large number of modelers overpowers the benefits), various non-linear models were considered and applied to the data set. A similar argument is made for the second type of model using the average number of features per row. One such approximation, based on the MichaelisMenten equation [111], offers a better model to regress the experimental data and provide a prediction for parts with numbers of features up to 20. The MichaelisMenten models, shown with the red lines in Figure 4.7, offer 2.37 and 2.72 times more predictive power with R^2 values of 0.153 and 0.205, respectively. Not only do these models offer a more accurate prediction for the optimal number of users, but they are also characterized by a more feasible non-linear trajectory consistent with literature on team or group size and performance [16,39]. The Michaelis-Menten model for optimal number of team members vs. number of part features is:

$$TeamSize_{Optimal} = \frac{3.77Features}{2.36 + Features} \tag{4.3}$$

where *Features* is the total number of features in the part. The Michaelis-Menten model for the optimal number of team members vs. average number of features per row of the part's feature dependency tree is:

$$TeamSize_{Optimal} = \frac{4.22Features_{PR}}{2.36 + Features_{PR}} \tag{4.4}$$

where $Features_{PR}$ is the average number of features per row in the part's feature dependency tree. Of course, the models shown in Equations 4.3 and 4.4 only apply in the domain and range of the test data, that is, for parts with fewer than 20 features and teams with one to four members.

Another way of looking at the ability of the proposed models' predictive power is to consider time to completion vs. feature count (or average number of features per row) by size of team. The results of this analysis are shown in Figure 4.8.

As demonstrated in Figure 4.8, the number of features shows a positive correlation with time to completion. These correlations were statistically significant, with p-values less than 0.05 in all cases except for the 2-user teams (p = 0.08). It is also important to note the increase in R^2

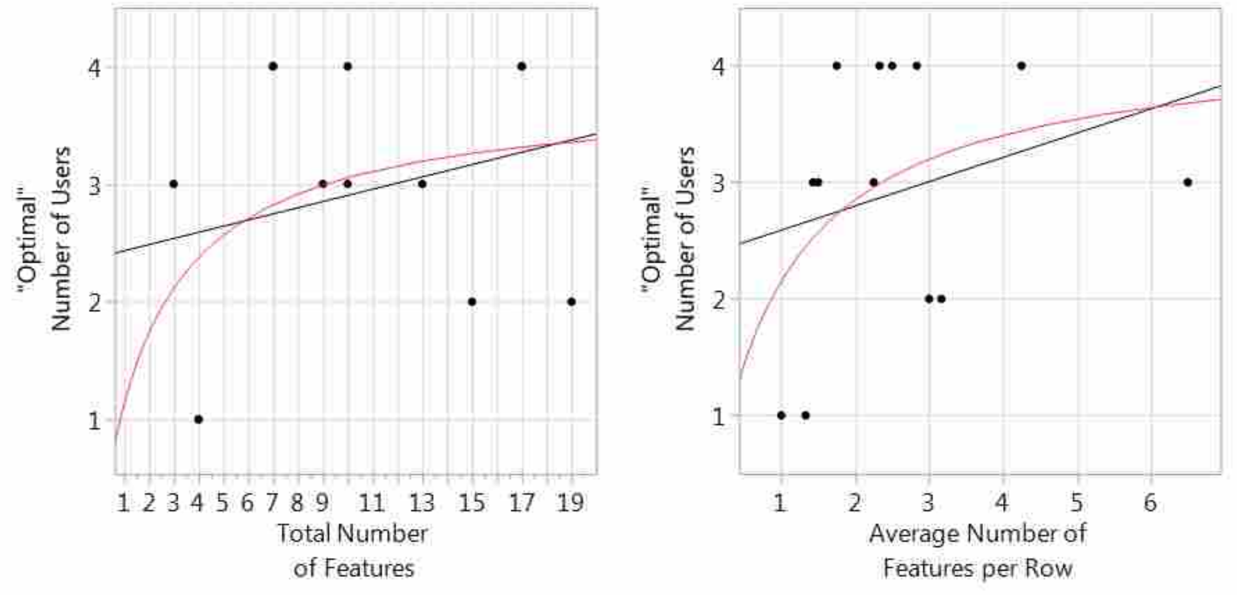


Figure 4.7: The optimal number of teammates by the total number of features, and by the average number of features per row (first-order linear regression (red), MichaelisMenten model (black)).

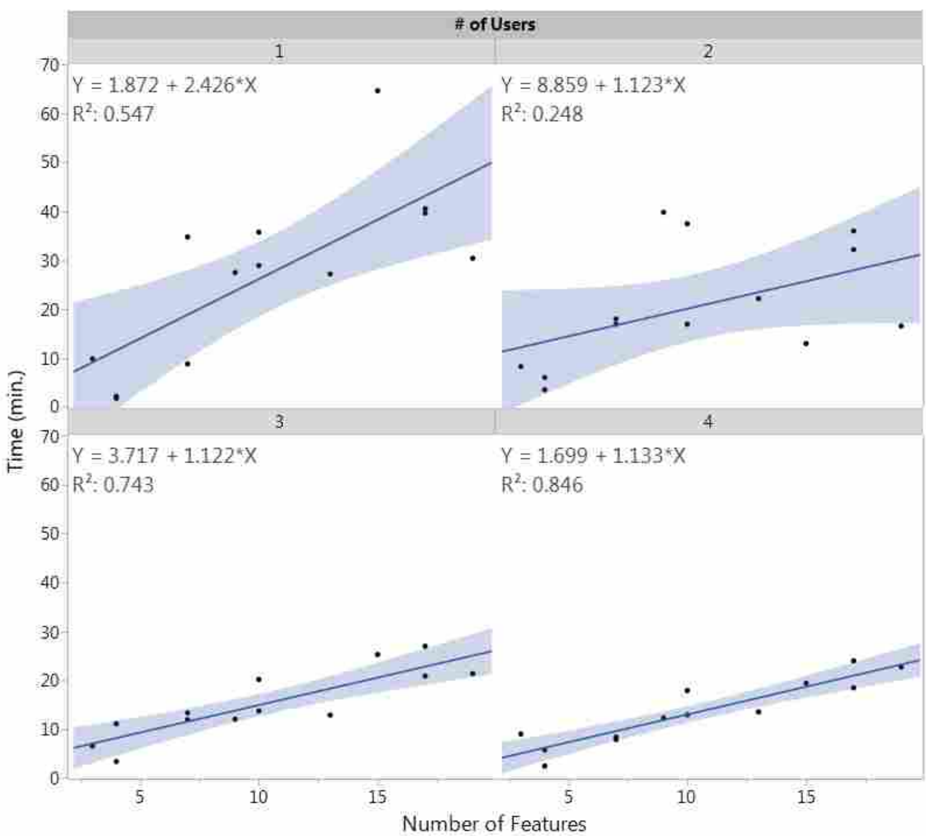


Figure 4.8: Time to complete each part vs. the number of features by the size of each team with 95 percent confidence intervals, linear regression equations, and R^2 values.

values as the size of the team increases. Statistical results for comparing completion time with average number of features per row yielded similar, but weaker results, with p-values ranging between 0.08 and 0.16.

4.6 Discussion

Results of our analysis show that the proposed models using the number of features and the average number of features per row do correlate with the optimal number of users, although weakly. It is likely that more repetitions of the same parts, and by larger sizes of teams (i.e. greater than four), will be necessary to fully validate these models statistically. Furthermore, the parts used were all primarily simple with respective to the total number of part features (i.e. less than 20). Team behavior and performance may be different with more complicated parts and offer more stable effects. Increasing the number of parts tested (n) will also increase the validity of the models proposed.

However, it was observed that MU teams may allow more accurate prediction of time to completion for a model of a given size (feature count) and found to be statistically significant in most cases. This finding matches our observations in other studies and experiences, such as the Modeling Competition (see Figure 2.6). One explanation for this phenomenon may be that teammates tend to complement each other's skill sets so that, where one user is less knowledgeable or skilled, other users can compensate with the needed knowledge, skill, or ability. Clear instances were observed where MU teammates learned from each other's modeling techniques during the experiments. The following sections describe some of the findings from these observations.

4.6.1 Quality Difference for Simple Parts

It was initially predicted that small, simple parts, such as those we classified with 10 or fewer features, would see little benefit from being modeled by a MU team. However, we observed that in some cases, while MU teams completed their simple parts more slowly than single-user teams, they also greatly increased the quality of the part.

The Cup is one example of when larger teams which took longer to model the part than the single user team. Despite efforts to control for quality, MU teams often insisted on including a

Figure 4.9: The level of detail included in the model of the cup generally increased with the number of users.

higher level of detail in their part, as shown in Figure 4.9. From the beginning of their modeling efforts, some MU teams seemed to have a sense of obligation to involve as many of their users as much of the time as possible. This led to teams altering their modeling strategy to make more, simpler features and/or consider strategies such as subtractive modeling to allow more users to contribute to the model simultaneously. A ratio of features added per minute of modeling time shows that even though the two and three user teams were much slower than the single user team, the number of features added per minute of the two of the MU teams were higher than the single user team.

4.6.2 Case Studies

Although many parts were expected to be suitable for multi-user teams and the experiments confirmed our predictions, a few unexpected results did occur. Those that met our expectations included the Car Door Panel, Fan Housing, Gear Pump Housing, Mining Machinery, Pump Casing, QuadCopter Arm, and Tablet Mount Arm. The Tray and Airplane Rib, two parts with the highest number of features (more than twice the average number of features of all the others), performed poorly with MUCAD teams in the experiments. Completion times for each team size for each of these nine aforementioned parts are shown in Figure 4.10.

Several parts, such as the Fan Housing, and Pump Casing appear to demonstrate Brooks style curves. Others, such as the Car Door Panel and Tablet Mount Arm, could also potentially be Brooks curves, but with their optimal points at a higher number of team members than tested. The Tray and Airplane Rib do not match these trends. In fact, the Tray part's completion time remains relatively flat for team sizes of one to three users, and finally increases with four users. This is opposite of our initial predictions that the Tray would be very suitable for MU modeling considering its large and widely branching tree structure.

After review of the video and audio recordings of the Tray part's teams, we discovered a large difference in way the single user modeled a few important portions of the part compared to the MU teams. For example, to add angular draft to the multiple negative extrudes in the part, members of the three-person team specified the amount of draft as part of each extrude feature. Meanwhile, the single user quickly created many simple extrudes, and then, using the draft feature, returned and applied draft to large numbers of extrusions at a time. This technique served the single user especially well, perhaps unknowingly, on one particular portion of the Tray, considered more complex. On the three-person team, the contributor who worked on the same portion, despite having the second fastest speed-test time, struggled significantly. In the end, he spent more than double the time to finish the section as the single user. Members of the four-person team experienced similar challenges. We suspect that the style of this single-user may be rare and that additional repetitions would reveal the Tray to be a strong candidate for MUCAD teams as originally predicted.

The observations of the teams modeling the Generic Airplane Rib part, also predicted to be suitable for MUCAD, revealed some interesting insights. The single-user was able to use a spline to model a satisfactory airfoil shape in roughly four minutes. For contrast, the four-member team decided to have each team member attempt to sketch an airfoil and then choose the best among the designs. After that effort failed, one team member went onto the internet, found a set of coordinates for a NACA airfoil, downloaded it, and created points for a spline. This entire process took approximately 12 minutes and significantly delayed the team's completion time. Based on these observations, we again suspect that with repetitions, this part would be shown to be a strong candidate for MUCAD teams.

4.6.3 Derivation of Principles

Several principles regarding MUCAD teams can be derived from the preceding research, tests, and observations. They include:

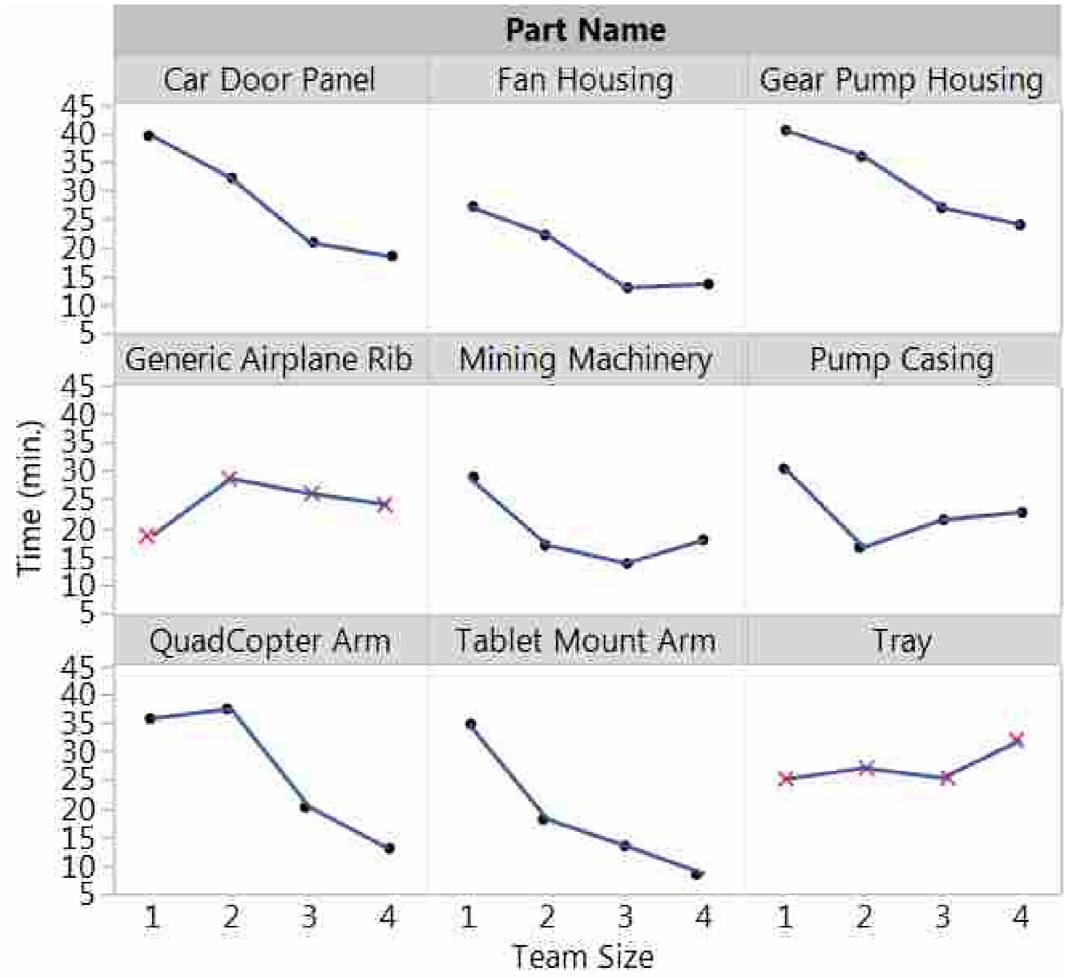


Figure 4.10: Completion times for each team size for the nine parts considered.

- Developing and classifying parts according to a taxonomy enables better understanding of part designs in the context of MUCAD teams.
- Parts which display a linear feature dependency tree structure are not good fits for MUCAD teams regardless of the number of features or complexity.
- MUCAD is not appropriate if the time to plan, organize, and administer the MUCAD team exceeds the time for one client to complete the CAD design. This assumes that design specifications are clear, that the part complexity does not require design or manufacturing engagement of other technical specialists, or the MUCAD session is not intended as a training session.

- By analyzing the type of part to be modeled, we can predict the optimal number of users.
- Use of MUCAD teams significantly improves the ability to predict how much time a part will take to model compared to using single user CAD (see figure 4.8).

CHAPTER 5. MAXIMIZING POTENTIAL PERFORMANCE WITH A PROFILE AND TEAM FORMATION SYSTEM

5.1 Introduction

Another important method by which to maximize potential performance of a virtual, MU-CAx team is to optimize the combination of people, with their different skills and characteristics, who make up the team. An ideal combination will optimize the team's overall score in each of the fundamental areas discussed in the background section. This leads to the hypothesis that teams which utilize the basic principles of optimizing their organization according to the fundamental areas will be more successful than other teams.

5.2 Experiments and Demonstrations

I attempted to validate the hypothesis and demonstrate its potential through multiple approaches:

- An experiment based on the principles of profile-based team formation with the 2013-2014 AerosPACE program teams
- A demonstration of using a web-based profile and team formation system to allow members of the 2015-2016 AerosPACE program to intelligently form their own teams
- A demonstration of using a genetic algorithm to optimize team member selection
- Highlighted findings from the modeling competition experiments

5.2.1 AerosPACE Program

Aerospace Partners for the Advancement of Collaborative Engineering (AerosPACE), a program sponsored by the Boeing Company, is one example of how industry and academia are attempting to adapt to the changing environment in which design and manufacturing occur (Becar & Gorrell, 2015; Cannon, Cunningham, Inouye, Stone, & Zender, 2015; Gorrell et al., 2014; Richey, Zender, & Schrage, 2012; Zender, Schrage, Richey, & Black, n.d.) and served as an important test and demonstration vehicle for this research. In the program, students from various universities from around the U.S. majoring in mechanical engineering, aeronautical engineering, manufacturing, and other related fields of study are combined into teams with experienced professors from the involved universities as coaches to design, build, and fly Unmanned Aircraft Systems (UASs). This organization, involving students with different backgrounds, fields of expertise, university schedules, and working from distant locations, is meant to imitate, albeit in a miniaturized fashion, the situation industry is experiencing as teams become increasingly virtual.

5.3 Experiment to Validate Principles of Profile-Based Team Formation

One effort to validate the idea that optimizing levels of the fundamental areas on a team would improve team performance involved the 2013-2014 AerosPACE program. Students participating in the the capstone course program were placed on one of three teams with members spread across various universities. Half of the students on each of the three teams were located at one university and the rest of the team-members worked from one of at least two other universities. These two groups became known to the researchers as the "core" team members, and the "non-core" team members, referring to whether or not the person was a student at the university with the most students on the team. The reason for having cores was that faculty felt it would facilitate the manufacturing portion of the project by having a larger number of people physically present in one location to work together on assembling the portions of the design created at different locations. See Figure 5.1.

Given the importance of team composition in influencing team performance [66], we wished to investigate its effects on virtual teams of engineering design students using the AerosPACE program. During the organization of the course, the question was posed, "How should individual students be allocated to each team, and how should each team organize its sub-teams, or IPTs?" We decided to investigate several items related to virtual team organization. The major hypothesis of this study was:

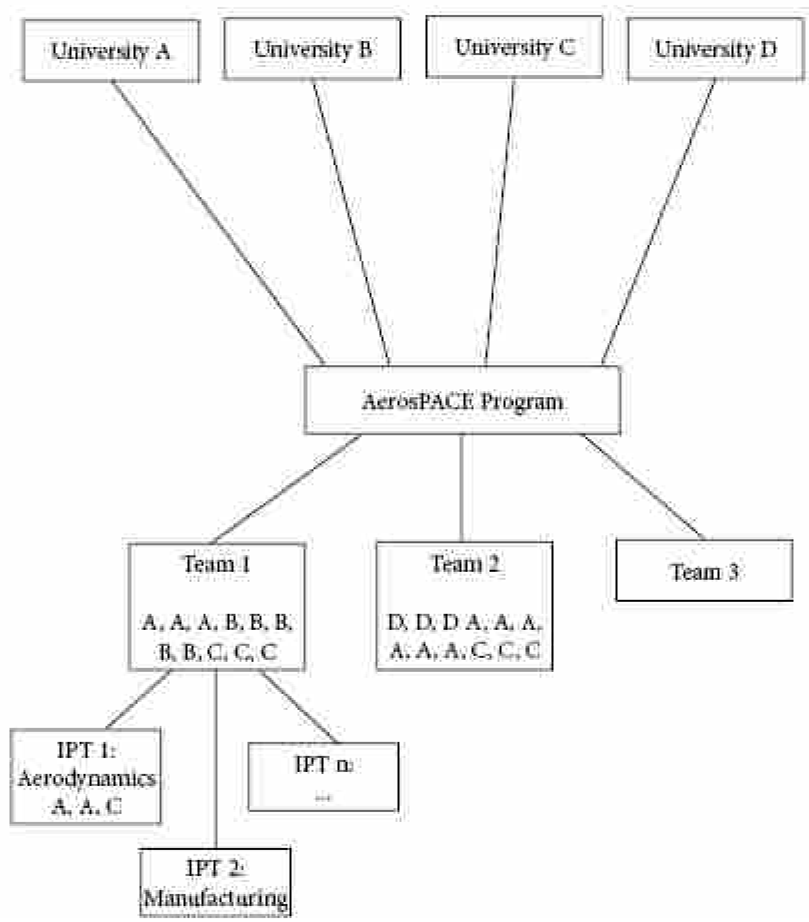


Figure 5.1: Students from various universities were distributed to each team. Each team then created sub-teams, or IPTs to work on specific portions of the project.

1. Teams organized using profile-based team formation methods will be more successful in at least one method of measuring success than teams utilizing more traditional organization methods, such as ad-hoc or hierarchical methods.

Several research questions were also investigated that were related to this main hypothesis. These included:

1. Will students from different universities rate their levels of satisfaction with their team differently?
2. How will core students differ in their satisfaction with their teams compared to non-core students?

3. What correlation between involvement in previous activities and the average peer ratings students receive from each other in the fundamental areas?

4. Will students who score higher on the MPVR also be ranked higher by their peers in the Technical Skill fundamental area?

Measuring Team Success

In order to measure how successful teams of students were in the 2013-2014 AerosPace program, "success" had to be defined and a method for measuring that definition had to be identified. MacMillan et al. measured the success of teams in their experiments by examining if teams completed assigned tasks and by assigning subject-matter experts to observe and evaluate team behavior [11]. Brannick et al. describe measuring a team's success by one or two measures: "process" or "outcome" [112]. Process, according to the authors, is concerned more with interpersonal elements of teamwork while outcome has more to do with whether or not the team actually accomplished the goal or goals they set out to accomplish. Levi and Hackman argue that there are three ways to measure team success: completion of the task, the satisfaction of team members, and the learning or improvement of individuals on the team [9, 46].

To explain why the team's satisfaction is important as a measure of team success, Levi gives the following example with firefighters:

> "Obviously, completing the task or putting out the fire is an important criterion of success. However, it is also important that the crews maintain a good working relationship and the crew members do not get injured in the process. Extinguishing the fire is important, but so is preserving the ability of the team to fight future fires."

Lin et al., found that team performance ("putting out the fire") is positively correlated with team satisfaction [113]. Hertel et al., in his work on methods of characterizing virtual teams and individuals, suggests studying satisfaction ratings of team members [114]. With these sources as guiding precedents, we selected team satisfaction as the primary measure of success for this study. We recognize that there are other important ways of measuring team success and will briefly mention aspects of teams' performance related to the research. However, our main focus will be on team member satisfaction.

Developing Individual Profiles

As noted in the background section, there are many ways to measure the each individual in the five fundamental areas (Motivation, Technical Skill, Social Skill, Leadership, and Logistics). However, only certain of those methods of measurement are available or useful at certain points in time for an organization. For example, in the case of the AerosPACE program, when the three teams were initially being formed, asking individuals to rate their peers would not have been very helpful since most of them did not know each other, even if they were from the same university. Thus, in this experiment, gathering information about individuals for the purpose of forming teams and IPTs was limited to methods such as self-reporting, use of pre-validated tests, and registering information from outside sources. Peer evaluation did take place during the project, but this data was not used to help form teams.

Work by Kaufman et al. validated two of the primary methods used to measure individuals in this research self and peer ratings. The researchers compared self and peer-ratings of university students in chemical engineering courses to each other and to the grades students received in the course. Their research shows that, despite faculty concerns that students would inflate their self-ratings, in fact, students tended to under-rate themselves compared to their peers. Significant positive correlation was also found between peer-ratings and course grades [115].

One method of testing individuals which we employed was a shortened version of the Purdue Visualization of Rotations Test, originally developed by Guay [60]. To reduce the survey load on students, we created a modified, shorter version of the test to administer to the capstone course participants called the Modified Purdue Visualization of Rotations (MPVR) test. See Figure 5.2 for an example. At the top, the figure shows an object, which is then rotated to a new position. Below that, a new object is shown. The student must then select from among options A through E the option whose orientation matches the same rotation demonstrated in the example at the top of the question.

Each student participating in the course agreed via Institutional Review Board (IRB) consent form to be a research subject and complete various surveys and interviews. The primary method of this research was via online survey. In person, or web-conference personal interviews and in-person observation were used in addition to the online surveys.

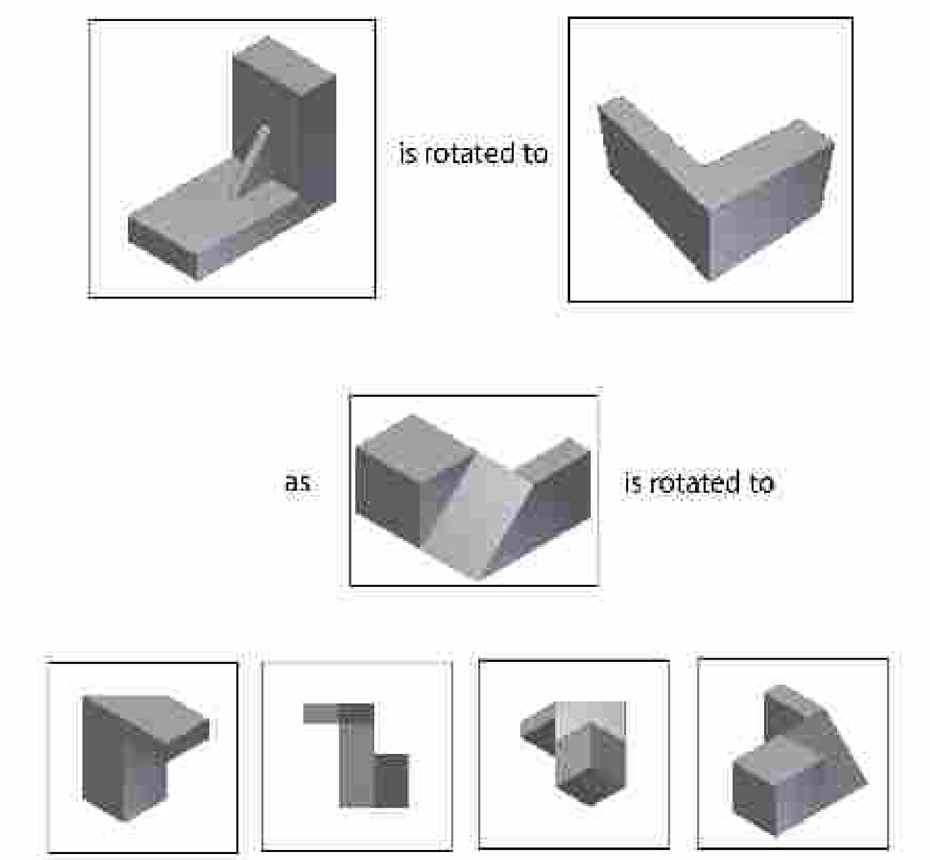


Figure 5.2: Example question from the shortened version of the Visualization of Rotations test.

Students completed various surveys at different times during the two-semester long project as part of the research. Table 5.1 gives the basic time-line and descriptions of the surveys used.

The surveys used many scale based questions such as, Think of the team that you are part of. How satisfied are you with your team? Very Dissatisfied, Dissatisfied, Neutral, Satisfied, Very Satisfied or the example shown in Figure 5.3, which asks students to rate their CAD skills.

Other questions required multiple choice/single response, multiple choice / multiple response, or text response. The surveys served multiple purposes. First, the Initial Survey and the MPVR allowed us to create a preliminary profile of each student according to the fundamental areas: motivation, technical skill, social skill, leadership ability and logistical considerations. Technical skill was, necessarily, sub-divided into various categories such as CAD, CFD, FEA, manufacturing, etc., as well as a "general" category. Survey items that contributed to student scores in each area included items such as:

Table 5.1: Outline of surveys used

Survey #	Survey Name	When Administered	Description / Notes
1	Initial Survey	Beginning of Fall Semester	Recorded demographic information, self-reported interests and skill levels in the fundamental areas
2	Modified Purdue Visualization of Rotations Test (MPVR)	Beginning of Fall Semester	A shortened, slightly modified version of the Purdue Visualization of Rotations test (Guay, 1976) was given to students as part of the assessment of Technical Skill
3	IPT Survey	Early Fall Semester	Team 2 only used to organize Team 2's IPTs with profile-based methods (see Team 2 IPT Organization Method subsection below)
4	Team Evaluation 1	Middle of Fall Semester	Asked students to rate satisfaction with team
5	Peer Evaluation 1	Middle of Fall Semester	Asked students to rate teammates in fundamental areas
6	Team and Peer Evaluation 2	End of Fall Semester	Asked students to rate satisfaction with team and to rate teammates in fundamental areas
7	Team and Peer Evaluation 3	Middle of Winter Semester	Asked students to rate satisfaction with team and to rate teammates in fundamental areas
8	Exit Survey / Team and Peer Evaluation 4	End of Winter Semester	Asked students to rate satisfaction with team and to rate teammates in fundamental areas and for feedback on course.

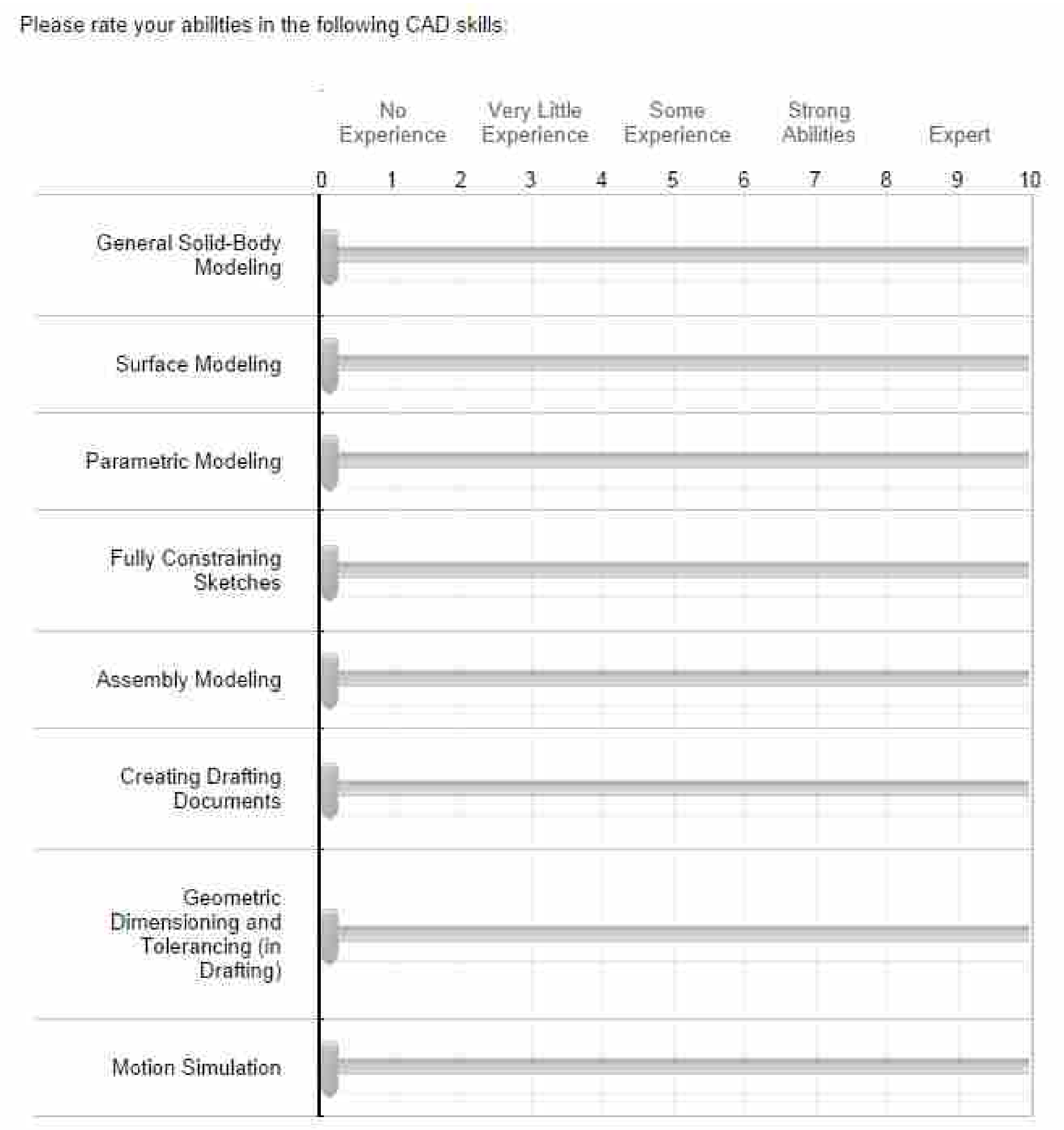


Figure 5.3: An example of one question from the Initial Survey, which used a Likert-like scale to ask respondents to describe their own CAD skill level (part of the Technical Skill fundamental area)

- Motivation
  - Self-rated interest in various topics related to the course, such as aircraft design, structural design and analysis, manufacturing, materials, etc.
  - Self-rated interest in improving skills in topics related to the course
  - Selection of items that influenced student to apply to participate in course. (If a student selected an item such as "required for graduation" no addition was made to the student's motivation score, while selecting an item such as, "It sounded challenging" added to their score).
  - Self-rated motivation to do well in course
- Technical Skill - CAD:
  - Score on MPVR test
  - Self-rated CAD skill in areas such as parametric modeling, assembly modeling, Geometric dimensioning and tolerancing, etc.
- Technical Skill - Computational Fluid Dynamics (CFD):
  - Self-rated skill in:
    * Meshing and grid generation
    * External Flow
    * Post-processing / Visualization
  - Self-rated overall familiarity
- Technical Skill - Manufacturing
  - Self-rated experience levels in areas such as metals manufacturing, plastics manufacturing, woods manufacturing, computer aided machining, etc.
- Social Skill
  - Preference for working in teams

  - Self-rating of skills such as listening, resolving conflict, tact, trustworthiness, general communication, etc.

- Leadership
  - Preference for acting in leadership positions in groups
  - Self-declared rating of how respondent felt others would rate his/her leadership abilities
  - Self-reported experience in leadership positions on clubs, teams, or other groups

Each item that added to a student's score in a given area was totaled, giving a score for each area, including a "general" technical score that included all sub-areas, and can be seen in Figure 5.4. Using this information, we organized the three teams so that each team had similar levels of total skill in each fundamental area and could thus be reasonably compared later. Some factors turned out to be more constraining than others. In particular, students with significant skill in using CFD tools were rare. Thus it was necessary to make a concerted effort to equally distribute students with this skill. Figure 5.4 shows the results of our efforts to evenly distribute these different attributes across the teams. Each team also had similar access to resources such as computer labs, manufacturing equipment, and coaching from experienced professors and Boeing personnel.

After completing this distribution, each team was formed and had to decide how to organize its members into sub-teams, or IPTs to work on specific portions of the project. While each team had slightly different IPTs, most shared a similar set, including aerodynamics, manufacturing, control systems, weight and balance and others.

One team, Team 2, used the profile method described in this paper to organize its IPTs. The other two teams used more traditional methods to organize their IPTs. Professors and students on Team 1 chose to use a mostly hierarchical structure, with graduate students at the top of the hierarchy selecting how to organize the team based on their judgment. Students and professors on Team 3 chose to use an extemporized method to organize its IPTs, usually by simply taking volunteers to work on each IPT as the work came up during the project.

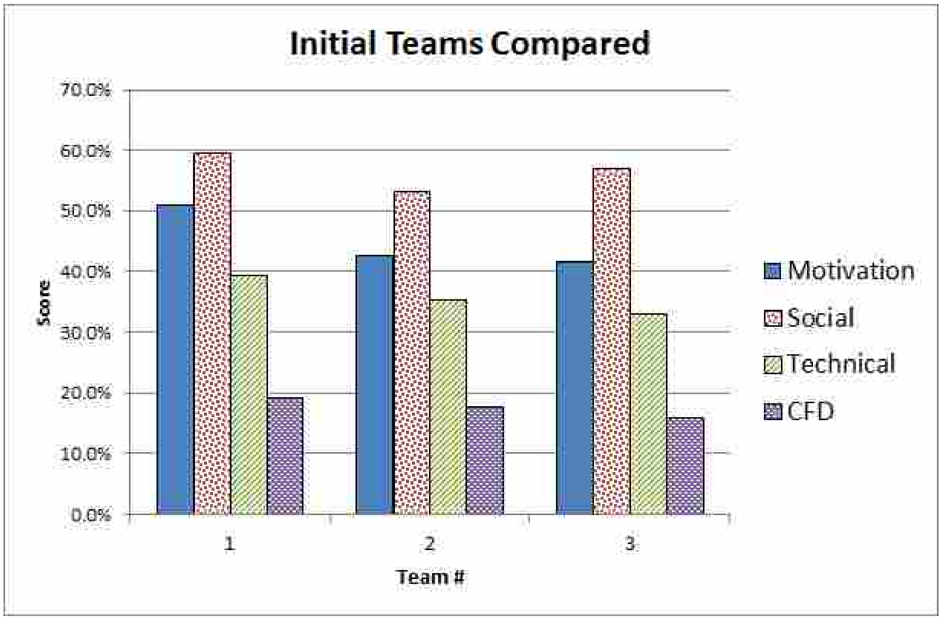


Figure 5.4: Teams were organized so that each had similar levels of skill in the fundamental areas. As well, Computational Fluid Dynamics (CFD) was found to be a particularly rare, important technical skill, so we attempted to ensure that all teams had a sufficient level of that expertise.

IPT Organization of Team 2

To attempt to avoid the potential pit-falls of ad-hoc teams described above and validate hypothesis one, we worked with Team 2's coach and student team leader to organize the team's sub-teams or IPTs by creating a profile of each team member using the following process, which is similar to Sauer and Arce's suggested method [66]:

1. Gather data from student team leaders and team coach about the tasks what IPTs would be created and what each IPT would be assigned to do
2. Gather information about each team member's interest level and skill level in each of the IPTs via an online survey (the IPT Survey), enabling a more detailed view of each team member's motivation and technical skills in specific areas. The IPT survey included a section for each IPT which contained the following descriptions and questions:
   (a) A brief description of the type of work performed by the IPT. For example, "The Aerodynamics IPT will work on the aerodynamic design of the aircraft including the wing

profiles and surfaces, culminating with high fidelity Computational Fluid Dynamics (CFD) analysis of the design."

(b) Self-rating of interest in belonging to the IPT to determine motivation for the given IPT. Clarification was made that previous experience or skill in the area was irrelevant for this question.

(c) Self-report of previous experience with the topic (classes taken, grades received, projects, internships, etc.) to determine technical skill in the topic

(d) Self-rating of interest in being the IPT lead

3. Process and present the information gathered through the survey to advise the student team lead of Team 2 (under the direction of the faculty coach) how to assign team members to each IPT by considering, in order, each of the following:

   (a) Motivation: To be considered for a position on an IPT, a student first had to express interest in being part of a given IPT (for example, structures or manufacturing)

   (b) Technical Skill: Students who were interested in being part of an IPT were next compared based on relevant skills and training (experience on similar projects, related courses and grades, etc.)

      i. Educational Clause: Given that the project was part of an educational course, students who expressed strong levels of interest in a given IPT but may not have had extensive experience were considered for a position on the IPT

   (c) Leadership Identification: Students who expressed interest in being the lead for each IPT were identified

   (d) Logistical Balancing: After identifying students who were qualified for the different IPTs and leadership positions, consideration had to be given to having the right number of students on each IPT and ensuring that each student was involved in neither too few nor too many IPTs. It was also necessary to spread the responsibilities of leading each IPT among the students for both logistical and educational purposes. As well, the geographic location of physical items had to be considered. For example, it was necessary to ensure that at least some students on the Manufacturing IPT were at a university with the needed shops and labs.

4. Recommendations were made to the student team lead and faculty coach of Team 2.

To measure success according to how satisfied team members were with their teams, throughout the project, each participant was invited to complete four surveys (surveys 4, 6, 7, and 8 in Table 5.1) in which students were asked to rate their satisfaction with their team on a 1-5 Likert scale where 1 = Very Dissatisfied, 2 = Dissatisfied, 3 = Neutral, 4 = Satisfied, and 5 = Very Satisfied. Similarly, peer evaluations of teammates in the fundamental areas were performed in surveys 5, 6, 7, and 8. A web-based, Likert-scale method was also used by Ohland et al. in their related research on using peer evaluations in student teams [116]. It could be asked why we did not simply use the CATME team formation and peer evaluation tools. One reason is that at the time we were not fully aware of the system. As well, the types of questions available in the peer evaluation portion of the CATME tool are limited and did not directly match the items we wished to consider.

Results

Results are presented in order, starting with the main hypothesis and followed by the research questions.

Hypothesis 1 The first and main hypothesis was that teams organized using a profile-based team formation method would be more successful in at least one method of measuring success than other teams. Initial results seemed to indicate that Team 2, which was organized using a profile-based team formation method, had a higher satisfaction rating than Teams 1 or 3 (see Figure 5.5 and Table 5.2). Figure 5.5 shows the average level of satisfaction of each team throughout the course. As can be seen, Team 2's average satisfaction was consistently higher than the other two teams. When averaging all ratings from all surveys, the average satisfaction rating (out of 5) for each team was: Team 1 = 3.96, Team 2 = 4.63, Team 3 = 3.86.

Observing Figure 5.5, it also can be seen that, generally, students' satisfaction with their teams increased over time. Each team did, however, have some period in the year during which their satisfaction decreased. For Team 3, the period between the first and second rounds (surveys four and six from Table 5.1) seems to have been particularly difficult, while for the other two

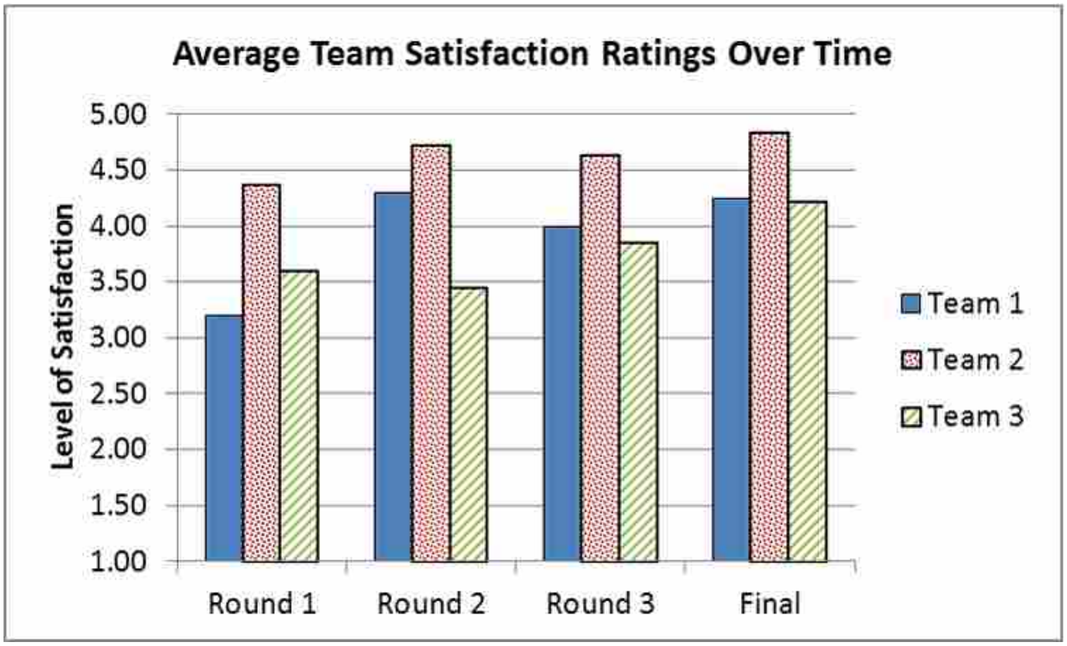


Figure 5.5: Throughout the course, Team 2's average satisfaction rating was higher than the other teams

teams, their ratings decreased a little later, in the third round. This may represent the teams' progression through Tuckman's classic "forming, storming, norming, performing" process [117]. Future research would be necessary to confirm this possibility. In any case, Team 2's levels of satisfactions were consistently higher than the other two teams.

Statistical analysis confirms that Team 2's higher average ratings were significant. To perform a Fisher's Protected LSD multiple comparison test, first, two outliers, which negatively affected the normality of the sample distribution and can be seen in Figure 5.6, were removed. This allowed equal variance to be assumed. The new mean values for each team were: Team 1 = 4.14, Team 2 = 4.63, Team 3 = 4.01.

Then, an analysis of variance (ANOVA) with an alpha level of 0.05 rejected the null hypothesis that all teams had the same mean value ($p = 0.03$) and established the multiple comparison as "protected" [118]. Next, an Each Pair Student's t-test with an alpha level of 0.05 indicated that Team 2's advantages over Team 1 and Team 3 were statistically significant. The p-values for the comparisons between each pair (alpha = 0.05) can be seen in Table 5.2.

As can be seen in Table 5.2, the p-value related to the difference between Team 2 and Team 3's average team satisfaction ratings as well as Team 2 and Team 1 is much less than 0.05,

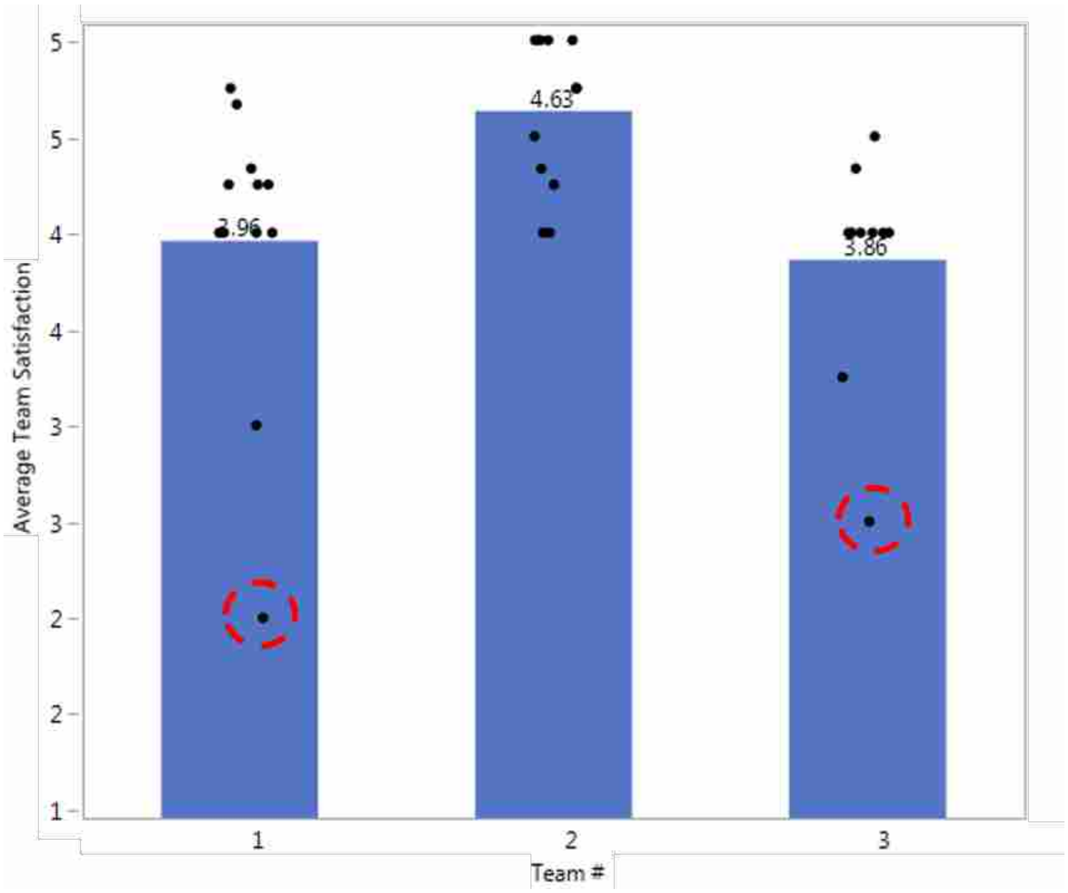


Figure 5.6: Average team satisfaction for each team, shown with bars, and individual average team satisfaction shown with points. Two outliers which were removed are shown in dashed circles.

Table 5.2: p-values when each team is compared to each other team using Fisher Protected LSD each pair t-tests

Team	Team	p-Value
2	3	<0.01
2	1	0.01
1	3	0.49

Table 5.3: p-values when each team is compared to each other using the more stringent Tukey-Kramer HSD t-test

Team	Team	p-value
2	3	0.01
2	1	0.02
1	3	0.77

indicating that the difference is statistically significant. A similar result can be seen with the difference between Team 2 and Team 1. However, the p-value for the difference between Team 1 and Team 3 is much greater than 0.05, indicating that the difference between those two teams' ratings is very possibly due to random chance. The more stringent All Pairs Tukey-Kramer HSD test (alpha = 0.05) also confirms the significance of the difference between Team 2 and the other teams (see Table 5.3).

Removal of the two outlier points merits further explanation. Besides its negative effect on normality, the point on Team 1 also represents a student who was the only student on that team from that student's university. In an interview, this student explained that being the only student from his school was the reason for giving consistently low ratings. Having one team member who works alone from a remote location may or may not represent a common situation in virtual teams, but it was the only such situation in the capstone course, and thus could be considered an anomaly.

The point on Team 3 was removed solely because of its effect on the normality of the data, but it should be noted that including either of these points in a statistical analysis only increases the significance of the differences between Team 2 and the other teams. These data points were excluded from analysis of data regarding research questions one and two as well for similar reasons.

Research Question 1 Other ways of categorizing students and their potential correlation with varying levels of satisfaction were also investigated, including by what school the students were from. Research question one asked if students from one university would give different ratings than students from other universities. An ANOVA test with an alpha level of 0.05 returned a p-value of 0.79. This suggests that no significant difference exists in satisfaction levels among students from the various universities. Means for each group were: BYU = 4.35, Embry Riddle = 4.12, Georgia Tech = 4.36, Purdue = 4.23. To further demonstrate the fact that no significant difference could be identified between how any two universities rated their team satisfaction, a

Table 5.4: Showing the p-values for each school compared to each other school from the Fisher LSD each pairs t-test for illustration

University A	University B	p-Value
BYU	Purdue	0.61
BYU	Embry-Riddle	0.40
Georgia Tech	Purdue	0.59
Georgia Tech	Embry-Riddle	0.38
Georgia Tech	BYU	0.96
Purdue	Embry-Riddle	0.69

Fisher LSD multiple comparison was performed. Each pair of schools' p-values can be seen in Table 5.4. No p-value reached below 0.38, indicating again that which university students attended seemed to have very little to do with how they rated their level of satisfaction with their team.

Research Question 2 Research question two asked if students who were core members of their team would have higher levels of team satisfaction than students who were not core members of their team. According to the survey responses, a positive correlation exists between being a core team member and higher levels of team satisfaction. The mean satisfaction score for core students was 4.43, while the mean score for non-core students was 4.11. The difference was statistically significant (p ¡ 0.05). If the points marked as outliers earlier are included, the variance between the groups becomes unequal, necessitating a slightly different t-test, but still resulting in a significant difference in the means (Mean Core = 4.43, Mean Non-core = 3.88, p = 0.03).

Research Question 3 This question asked if there would be some sort of correlation between activities students had previously been involved in and the ratings they received from their peers in the fundamental areas. While most comparisons yielded no significant correlation, one set of notable correlations came from investigating student's participation in sports and the average ratings they received from their peers in the areas of Social Skill and Motivation.

For the purposes of this study, a "team sport" was defined as a sport in which the team has a at least a moderate interdependence, as explained by Feltz et al. [119]. For example, sports like baseball and football have moderate levels of interdependence, while basketball or soccer would be considered to have high levels of interdependence. Meanwhile, track teams and swimming teams, although arguably "team" sports have lower levels of interdependence. To further explain: if a hurdler loses a race, it normally doesn't affect her teammate who throws shot-put the same way a setter missing the ball affects the outside hitter on a volleyball team.

A t-test with a 95 percent confidence interval shows that a significant difference exists between the Social Skill ratings received by students who reported having participated in at least one team sport and those who had not. The mean for those who had NOT participated in at least one team sport was 3.87, while the mean for those who HAD participated in at least one team sport was 4.17, p = 0.03.

If participation in one team sport is positively correlated with how one's peers rated one's Social Skill, the natural next question to ask would seem to be, "Does participating in more than one team sport increase the effect?" A t-test with a 95 percent confidence interval was performed to compare those who had participated in more than one team sport to those who had participated in one or none. Although a positive difference in average peer Social Skill rating does exist for those who had participated in more than one team sport (Mean for More Than One Team Sport "Yes" = 4.12, Mean for More Than One Team Sport "No" = 4.00), the difference was not statistically significant, with a p = 0.40.

How participation in team sports affected students' ratings in other fundamental areas was investigated. A t-test with a 95 percent confidence interval shows that although on average, students who had played at least one team sport were rated higher by their peers in the fundamental area of Motivation (Mean for those who Had NOT Participated in at least one team sport = 4.19, Mean for those who HAD participated in at least one team sport = 4.35), the difference was not statistically significant, with a p-value = 0.32. No correlation could be identified between team sport participation and the other fundamental areas.

Another interesting correlation was found between the total number of activities students had participated in and the average Social Skill ranking they received from their peers. "Activities" included team sports, non-team sports, and participation in organizations such as band, clubs, or other organized groups. A linear fit of Social Skill Ratings and the total number of activities a student had been involved in resulted in a positive correlation,

$$AveragePeerSocialRating = 3.946 + 0.017 TotalNumberofActivities \tag{5.1}$$

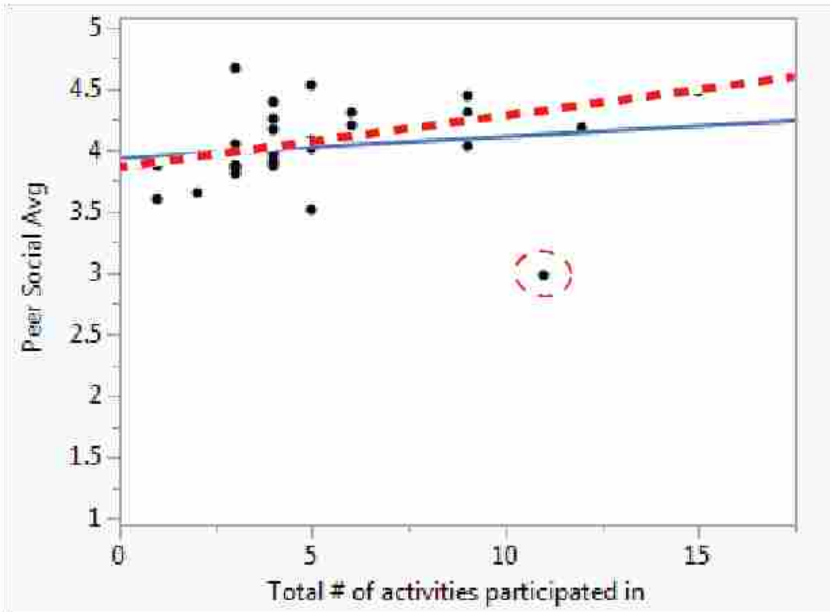


Figure 5.7: After removing the outlier (circled in red) the original correlation (solid line) became more positive, a better fit (dashed line), and statistically significant.

with an $R^2 = 0.03$ and a p-value of 0.41. The variable coefficient (0.017), R^2 value, and p-value cast serious doubt on the significance of the correlation. However, after removing the only outlier from the data set, the fit became

$$AveragePeerSocialRating = 3.860 + 0.043 TotalNumberofActivities \tag{5.2}$$

with an $R^2 = 0.23$ and a p-value of 0.01. Figure 5.7 shows the relative improvement in the curve fit after removing the outlier.

Research question four asked if students who scored higher on the MPVR would be rated more highly by their peers in the Technical Skill fundamental area. Students did tend to rate peers who scored higher on the MPVR higher in Technical Skill. A linear fit of scores from the MPVR to Technical Skill ratings gave a positive correlation,

$$AveragePeerTechnicalRating = 2.84 + 0.19 Score_{MPVR} \tag{5.3}$$

with an $R^2 = 0.24$ and a p-value of 0.02. Figure 5.8 shows the graph of the linear fit.

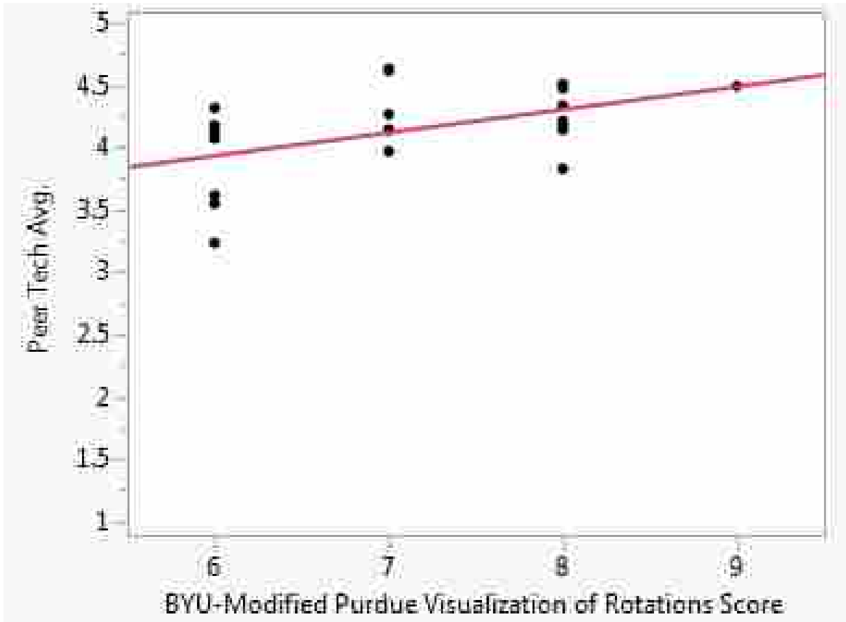


Figure 5.8: A significant positive relationship was found between student scores on the Modified Purdue Visualization of Rotations Test (MPVR) and their average Peer Rated Technical Skill. Note that no students scored lower than 6/10.

Discussion

A discussion of the results of the study is presented here in order of the hypotheses and research questions.

Hypothesis 1 These results support the idea that the profile-based team formation method helped Team 2 achieve higher levels of success than teams that organized their IPTs using more common methods. Students who were part of the team that used a profile-based team formation method to organize their IPTs ranked their satisfaction with their team higher than students on teams who used either hierarchical or ad-hoc IPT organization methods. The difference between Team 2 and the other teams was statistically significant according to both a Protected Fisher's LSD and Tukey-Kramer HSD.

Another method of measuring success, besides the satisfaction of team members with their team, is technical. In this case, technical success could be defined by whether the UAV designed and built by the team flew and met qualifications in the time allotted. We do not attempt a detailed analysis of this measure of success in this research, but it is worth noting that of the three teams, Team 2 was the first team to fly their final production vehicle. These results support the idea that the time and effort needed to gather the data and go through the process of organizing a team with a profile-based method are worth it.

Examining Figure 5.5, it is worth noting that while Team 2 maintained a higher average satisfaction rating throughout the project, the differences between Team 2 and the other teams were greatest at the beginning, with Team 1 and 3's last ratings being approximately equal to Team 2's first rating. One could speculate that using a profile-based method of IPT formation helped Team 2 to form a shared mental model of the team and the work to be done more quickly than the other teams, or in some other way jump-start their process of improving their team satisfaction.

Research Question 1 The results indicated that no significant difference could be found in satisfaction ratings between students from any given pair of universities involved in the capstone course. Since what university students were from did not influence how they rated their satisfaction, a substantial potential confounding factor has been neutralized.

Another interesting observation has to do with the fact that the majority of students in the capstone course were aeronautical engineering majors, and a minority (all from BYU) were mechanical engineering majors. Implied in the fact that no difference between universities could be found is also the fact that no difference between majors could be found. This finding should also be verified by more research. These results are important because they eliminate two potential sources of measurement variance. Educators and others charged with organizing and coaching distributed engineering teams can more confidently predict the reason for students' levels of satisfaction with their team.

Research Question 2 Having teams with core groups of students may have been desirable for manufacturing purposes, but it was suspected that it also may have hurt team success and detracted from having a true distributed team experience. Observations by faculty and researchers agreed that being core or non-core seemed to affect how "integral" to the team students felt and contributed to team disagreements.

In an interview with one student who was a non-core member of his team, the student talked about how the nature of having a majority of teammates at one location contributed to feeling less satisfied with the team as a whole. Since the schedules of the core students did not match well with the schedules of many non-core students, the core students began meeting on their own and making decisions that affected the entire team. The result was that some of those who were unable to attend felt estranged.

The most extreme case was the student who was the only teammate from his university. In interviews with this student, he indicated that, especially at the beginning of the project, he found it very difficult to coordinate and feel like he was a part of the team. He also felt a lot of pressure to represent his university well, since he was the only representative of his school. That pressure, he explained, was not all bad, since he felt it helped him perform to a higher level. In his opinion, that was, however, the only benefit to being alone on his team. While his teammates at other universities were able to easily do things like check each other's work and confirm meeting times, he had to coordinate everything via email or other electronic means, adding to his communication overhead. His favorite communication tools to overcome his challenge quickly became web-conferencing tools like Skype and Web-Ex, which allowed him and whoever he was communicating with to not only see and hear each other, but also share each other's screens. Even after discovering these tools, he said being the lone team member was still very difficult.

In conclusion, core and non-core team members appear to have had statistically significantly different experiences as part of a virtual engineering design team depending on whether or not they were part of the core group. This should be born in mind when organizing similar programs in the future.

Research Question 3 The statistically significant positive correlations between participating in at least one team sport and the ratings students received from their peers in Social Skill aligns with findings by other researchers. For example, Artinger and Barcelona, in separate studies demonstrate the correlation between participation in sports and effectiveness in other activities [120, 121]. Artinger et al. surveyed more than 300 university students involved in recreational athletic programs. They found that on a 1 (disagree) to 5 (agree) scale, the average rating for the statement "Participation in recreational sports improves my ability to work within a team" (reverse coded to address social desirability response) was 4.14/5.00. Barcelona showed that, among the college students he studied, participation in sports programs was a significant predictor of gains in team functioning in areas outside of sports.

The difference in Social Skill ratings between students who had participated in more than one team sport compared to students who had only participated in one or none was not statistically significant. It seems as though the benefit, with regards to social skill improvement, may level off after participating in one highly interdependent team sport. Acknowledging that the results of this study can only be directly correlated with the sample of this study and that correlation is not causation, this result may indicate a “threshold” for the effect participating in team sports has on the Social Skill levels of engineering design team members. Perhaps this result could imply that the benefit to Social Skill for engineering students of participating in a team sport is getting to know how to play as a team member, and that playing multiple team sports is redundant to that end. Knowing that playing a team sport has a positive effect on Social Skill could make it possible for team coaches or leaders to improve their team’s performance, either by searching out team members who have played a team sport, or by encouraging current team members to participate in a team sport.

Research Question 4 Students who scored higher on the MPVR were statistically more likely to be rated higher by their peers in Technical Skill. This implies that it may be possible to predict, based on the results of the MPVR or a similar test, how technically adept a team member will be, or at least how technically adept they will be perceived by their peers to be. Being able to more accurately predict an individual’s Technical Skill would be valuable for engineering design teams by reducing the time and effort needed to form teams of individuals with complementary skills.

5.4 Demonstration of Use of a Genetic Algorithm to form an Optimal Team

5.4.1 Introduction

In the AerosPACE 2013-2014 program year, Team 2’s IPTs were manually organized with the goal of optimizing each according to the fundamental areas. A draw-back to this method is that it required significant effort on the part of the organizer to sort through the various individual profiles and match individuals to IPTs in need of members. A more convenient option, especially if this type of method were to be deployed for a large organization and repeated often, would be to employ an algorithm to automate the selection process. To demonstrate the feasibility of this approach, a genetic algorithm was implemented to optimize the formation of an engineering design team, subject to various constraints.

From a pool of 50 candidates, the algorithm had to select a team of 12. Candidates each had ten characteristics, including location, technical skills, and social skill. Two fitness functions, one to optimize a team's social skill, the other to optimize a team's technical skill, were used to form a Pareto front of potential team configurations. The algorithm produced a Pareto Front of 13 teams.

This demonstration was based on a hypothetical situation: after the AerosPACE 2013-2014 project finished, Boeing wishes to hire a group of the students to design, build, and fly a UAV similar to the one each team developed during the project. To increase the candidate pool, and bring the total to 50 candidates, an additional school with 16 imaginary students (UCLA) was added. In this hypothetical situation, Boeing desires the students it will hire to remain at the location of their university (forming a virtual team) and assumes the team will be entirely staffed by these new hires (12 team-members). Some of the requirements for the team include:

- Hiring students from at least three different schools
- Not hiring fewer than 2 students from any school from which students are hired (experience has shown that teammates who are alone at their location experience significant difficulty compared to teammates with at least one other person co-located with them).
- Having at least one team-member of each gender
- Maximizing the social and technical skill levels of the team

How can Boeing avoid using ineffective, ad-hoc methods to find the optimal configuration for this design team? A genetic algorithm seems ideally suited to this type of challenge.

5.4.2 Procedure

The model for the algorithm was based on research performed during the AerosPACE capstone project and from other sources (see background section). Candidate team members were evaluated based on their scores in the fundamental areas:

- Motivation (level of commitment to the project)

Table 5.5: Candidate characteristics with descriptions

Category	Characteristic	Description
Motivation	Motvation	Average rating received on a 1-5 scale from self and peers
Leadership Ability	Leadership Raw	Average of rating received on a 1-5 scale from self and peers
	Leadership Percentile Rank	Derived from raw leadership score
Social Skill	Social	Average of rating received on a 1-5 scale from self and peers
Technical Skill	Technical (overall)	Average of rating received on a 1-5 scale from self and peers
	CFD Percentile Rank	Derived from self-declared skill and experience
	CAD Percentile Rank	Derived from self-declared skill and experience
	FEA Percentile Rank	Derived from self-declared skill and experience
Logistics	Name	Used to identify unique team members
	Gender	M / F
	Location	One of four campuses: BYU, PD, GT, ER, UCLA

- Technical Skill (level of skill/experience in various technical areas, level of education)
- Social Skill (includes ability to communicate with peers and collaborate effectively)
- Leadership Ability
- Logistical Considerations (location, gender, etc.)

Information on each student involved in the project was gathered in each of these areas. Two primary methods to gather this information were used: 1) self-report via online surveys, 2) peer review via online surveys. For the real students who participated in the AerosPACE 2013-2014 program, data was gathered from self-report and peer evaluation surveys (see Table 5.1). For the imaginary students from UCLA, synthetic data was created. Ten characteristics, identified and described in Table 5.5, were identified for each candidate.

Table 5.6: Comparison of Technical and Social Fitness functions

Characteristic	Technical	Social
Motivation	Maximize Team Average	
Leadership	Ensure that not too few/many leaders are on team	
Leadership Percentile Rank	Ensure at least two highly ranked leaders are on team, Maximize percentile rank of top 4 ranked candidates on team	
Social	N/A	Maximize Team Average
Technical (overall)	Maximize Team Average	N/A
CFD Percentile Rank	Ensure at least one expert is on team, Maximize expert percentile rank, Maximize team average percentile rank	N/A
CAD Percentile Rank	Ensure at least one expert is on team, Maximize expert percentile rank, Maximize team average percentile rank	N/A
FEA Percentile Rank	Ensure at least one expert is on team, Maximize expert percentile rank, Maximize team average percentile rank	N/A
Gender	Ensure at least one of each gender on team	Ensure at least one of each gender on team, increase gender diversity of team
Location	Ensure no location represented on team has only one student and that at least three universities are represented on team	

Pareto Front Development Characteristics as shown in Table 5.5 were identified and calculated for all 50 candidates. Although many different objectives could be identified, two important objectives in configuring a team are the team's technical and social skill levels [46, 122]. In order to identify a Pareto Front of possible designs, two distinct fitness functions were developed, one focused on maximizing technical skill, the other focused on maximizing social skill. The fitness functions are described in Table 5.6.

Some characteristics, such as Motivation and Leadership were considered common to both the Technical and Social fitness functions. In the Leadership characteristic, it was desirable to not only ensure that each team has enough capable leaders and that their leadership abilities were maximized, but also that the team doesn't have too many members with strong leadership abilities. The reason for this consideration is the desire to avoid the "too many chiefs and not enough braves" situation. Maximizing the leadership percentile rank of the top four ranked candidates was done in order to account for common leadership positions including Team Lead, Chief Engineer, and two Integrated Product Team (IPT, aka "sub-team") Leads.

In the Technical fitness function, at least one "expert" in each of the three technical sub-areas of CFD, Computer Aided Design CAD, and FEA are needed. An "expert" is defined in this case to be someone to have a percentile rank of at least 65 or higher. The average of the team in each of these technical sub-areas was also maximized.

At least one member of each gender is required in both the Technical and Social fitness functions. In the Social fitness function, additional fitness is awarded if there are at least two members of each gender on the team.

The Technical and Social fitness functions do not include each other's exclusive characteristics, as indicated in Table 5.6. Both fitness functions must ensure that at least three schools are represented on the team and that in no case is a team member the only member of the team at his/her location.

Development of the Algorithm The algorithm begins by generating 200 potential configurations of teams by randomly combining the 50 candidates into groups of 12 unique people per team. After these teams are configured, they are each evaluated by the social and technical fitness functions. The two fitness functions are used to determine a domination rank, and this rank is modified based on the "closeness" to other teams to prevent clustering (and increase diversity). This modified domination rank is used as the total fitness of the teams by which they would be ranked.

A modified tournament selection routine with a tournament size of 10 is used to find parents. The only difference from a standard tournament is that two parents are chosen in each round of the tournament to guarantee an even number of parents. After all parents are chosen, they are randomly paired with one another to produce children. Each set of parents produces 10 children, so that the total population size doubles. Elitism is employed as the parents and children compete with one another. After the children are created, the top 200 teams of the population are retained for the next generation and the rest are discarded.

The reason all parents are randomly chosen from a pool for mating, instead of having pairs chosen in the same tournament mate, is to increase the randomness and diversity of the

Table 5.7: Various characteristics of the algorithm

Algorithm Characteristic	Value	Notes
Mutation Rate	0.05	Can temporarily increase if designs stagnate
Population Size	200	Allows for large diversity
Tournament Size	10	Helps choose good parents
Number of children per generation	200 / round	Allows for better probability of increased fitness over parent generation
Number of Generations	up to 1,000, or after average fitness has not changed for the previous 10 generations	Normally ends at about 600 generations

children teams produced. A population size of 200 and a tournament size of 10 were chosen after experimenting with the algorithm and finding that size to converge the best.

Mutation was possible for each team member position. The base mutation rate was set at five percent, and replacement teammates are randomly selected from the set of 50 candidates. If the average technical and social fitness does not change from the previous generation, the mutation rate increases by one percent. This increase in mutation rate continues until the average social or technical fitness scores increase, at which point, the mutation rate resets to the base rate of five percent. This mutation scheme was employed in order to help escape local minima. The algorithm terminates when ten generations have passed without a change in the average fitness values. Algorithm characteristics are summarized in Table 5.7, and the code for the genetic algorithm's fitness functions is included in Appendix A.

5.4.3 Results

After roughly 600 generations, a Pareto Front of 13 potential optimized team configurations was produced, as seen in Figure 5.9. This front allows for "Design by Shopping Around", meaning, the organizer of the team can choose from among designs along the Pareto Front. For demonstration, we chose a team configuration that we felt balanced the social and technical aspects well (see Table 5.8).

Table 5.8: Team members on team chosen from the final Pareto front

Pseudonym	Motivation (0-4)	Leadership (percentile)	Leadership Raw (0-4)	Social (0-4)	Gender (M/F)	Location	Technical (0-4)	CFD	CAD	FEA
								percentile		
Julia Capulet	3.65	0.125	2.15	3	F	UCLA	2.60	0	0.956	0.869
Jules Vernal	3	0.062	1.9	2.5	M	UCLA	3.80	0.565	0.804	0.043
Ivan theGreat	3.2	0.333	2.55	3	M	BYU	3.60	0	1	0.869
Weixiao Xu	3.36	0.333	2.55	2.55	M	P	3.82	0.304	0.391	0.369
Ignacio Coral	2.89	0.27	2.44	3	M	P	3.11	0.565	0.195	0.369
Dylan Crawford	3.91	0.979	3.91	3.64	M	ER	3.73	0.304	0.543	1
David Louis	3.27	0.187	2.27	2.55	M	ER	3.09	0.304	0.369	0.456
Enrique Iglesias	3.82	0.812	2.45	2.55	M	P	3.27	0.782	0.043	0.521
Margaret Thatcher	3.8	0.958	3.55	3.6	F	UCLA	3.10	0.652	0.152	0.456
Bryce Whipple	4	0.479	3.4	3.4	M	GT	3.70	0.956	0.782	0.565
Enrique theEigth	3.8	0.958	3.7	3.6	M	BYU	3.70	0.304	0.826	0.086
Tom Cruise	4	0.479	2.8	2.7	M	GT	3.90	0.978	0.717	0.217

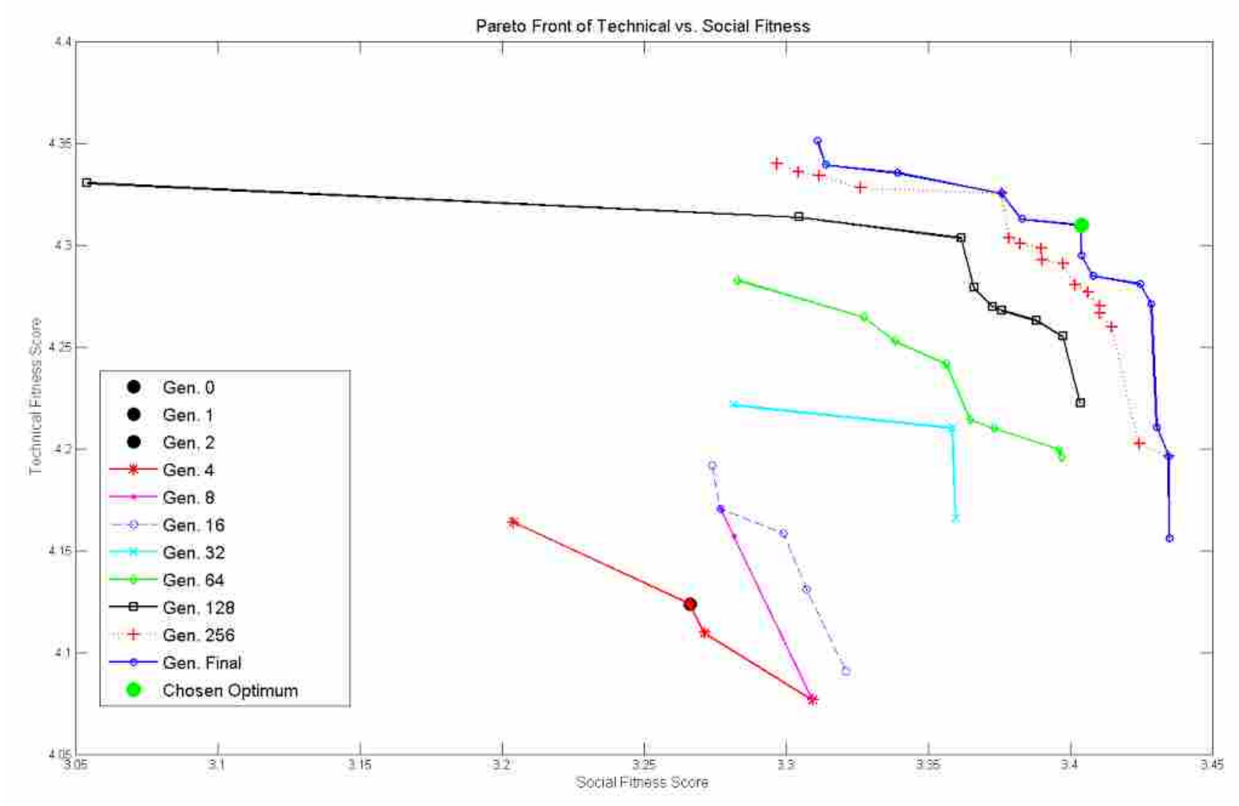


Figure 5.9: Pareto Front of Technical vs. Social Fitness for teams over 600 generations of our genetic algorithm. Teams progressively increased in both their social and technical fitness until reaching the final Pareto Front. The chosen optimum (green dot) represents the team chosen.

The development of the Pareto Front over several hundred generations, and as shown in Figure 5.9, shows several interesting characteristics. For example, Elitism is demonstrated in several instances. The first couple generations are dominated by one team configuration that survived on the Pareto Front until the fourth generation. Another design from the fourth generation survived at least until the eighth generation, and a different team from the eighth generation survived at least to the 16th!

The next clear demonstration of a team configuration surviving for many generations can be seen between generation 256 and the final generation. Here, at least two designs survived for hundreds of generations and made it onto the final Pareto Front. Similar to crocodiles that have survived since the time of the dinosaurs until today, relatively unchanged, these teams demonstrate how powerful and important Elitism is in finding the best possible designs using a genetic algorithm.

Selected Optimum Team The teams along the Pareto Front represent "the best of the best" of all possible team configurations. About a dozen teams were non-dominated and offer varying levels of technical and social skill. Members of the selected optimum team demonstrated a few trends that were worth noting. Nearly all were ranked by their peers as being highly motivated. The average leadership score (2.806) was almost exactly equal to the average leadership score of the entire candidate pool (2.805). This means the algorithm and fitness functions did a good job of ensuring that there were enough team-members to fill key leadership positions, but also enough team-members who are not leaders so that a "too many chiefs and not enough braves" situation is avoided.

Technical specialization seemed to be common. Many of the team members are the top ranked specialist in a given technical field, such as CFD, or CAD, but among the lower or even lowest ranked in other technical areas. Few team-members were simply "Ok" at all three technical specialties.

Interestingly, no one university dominated the selected optimal team. In fact, all universities are represented on the team. BYU and Georgia Tech tied for the most team members with three team members each on the team. Even though Embry Riddle only had four students total (compared to UCLA's 16) it also had two students on the team.

5.5 Demonstration of Use of a Web-based Profile and Team Formation System in the 2015-2016 AerosPACE Program

While an automated team formation system using an algorithm such as the one described above can certainly reduce the load on a manager charged with forming teams, one can anticipate that many managers would want to have a somewhat more detailed view of how their team is being organized and even be able to make individual decisions regarding who is on or off of a team. Allowing managers and team leaders access to each individual candidate's profile and a semi-automated tool or tools to form and evaluate potential teams is one method of enabling this type of team formation. As well, evidence in the literature suggests that team members, especially virtual team members, can increase levels of what Parker calls "Swift Trust" [16], an important ingredient for getting teams off to a good start, by presenting them with information to help them get to know their teammates and establish a shared mental model of who is on the team [123]. Here, I present a demonstration of a profile and team formation system that allowed virtual teammates to get to know each other better and allowed coaches and student team leaders to organize their IPTs using feedback and data aggregated from each student's profile.

By the Fall of 2015, the AerosPACE program had grown to include eight universities and the number of students involved had grown to 72. In order to keep team size at a manageable level, seven teams of approximately 10 students each were organized in a manner similar to the method used in the 2013-2014 program year, including completing a survey which provided data we used to attempt to make the levels of each team in each of the fundamental areas as similar as possible while meeting other program constraints.

As well, a web-site with a profile of each student in the program was created. The web-site, secured with unique log-ins and passwords for each student, coach, and researcher included different levels of access to data based on the log-in used. While faculty coaches and administrators could see all data on a given student's profile, each student could only see certain high-level attributes on his/her peers' pages.

Once teams had selected student team leaders, those students were given access to the semi-automated team formation tool on the web-site and encouraged to use it to organize their IPTs. Students actively used the profile system to get to know team members, both from their own university and from other universities, and to assist in forming their IPTs.

Profile and Team Formation System

The profile system was created based on the same principles as the profiles created during the 2013-2014 program year. A screen-shot of a student's profile, as it would appear to an administrator or coach can be seen in Figure 5.10.

As can be seen, the information is organized according to the fundamental areas. Data is automatically imported from Qualtrics (the online tool used to administer surveys). Percentile ranks are then calculated for each member of each team (against the other members of his/her team). Students can upload a profile image, view their own profile and browse the profiles of their teammates. When viewing a teammate's profile, the data visible is restricted to a much more basic set than seen in Figure 5.10. Peers can only see each other's profile image, Logistical data, Experience, as well as Technical Skill items in which the student ranked higher than 50 percent of

Figure 5.10: View of an AerosPACE student's profile (anonymized) as seen by a faculty coach or system administrator

his or her peers. Instead of listing scores and percentile rankings, the Technical Skill box simply reads, “Technical Skills (Good at):” and lists items such as, “CAD Skills, Propulsion Skills” and so on. Students identified as Team Leads (Chief Engineers, Team Leads, or Program Managers) were able to view profiles similar to what faculty coaches saw, but only for their team. It should be noted that, a profile in this system, while sharing some basic characteristics with profiles on popular social media platforms such as Facebook, differs markedly. First, the content is restricted to and categorized according to the fundamental areas. Second, most of the elements on the profile are only indirectly controlled by the person represented. This scope allows the profile to specialize in its purpose and may make it more similar to the customer profiles online companies such as Amazon create to attempt to cater their advertising efforts specifically to each customer [124].

Instead of helping companies like Amazon decide which products to advertise to site visitors, however, the information in the student profiles served to help team leaders as they tried to form more effective IPTs. In addition to simply browsing team member profiles, student team leaders were also able to access the IPT Former tool (seen in Figure 5.11). Near the top center of the screen-shot, student team leaders can select the IPT they wish to form from the drop-down menu. Then, they work from left to right. First, they select one or more team members to add to the IPT (from the left to the center column). When a student’s name is clicked, his or her photo and profile information relevant to the IPT are displayed in the bottom left corner. If the student is added to the “IPT Members:” column (center) the “IPT Statistics” column (far right) is updated to show the characteristics of the IPT with its new membership. Included in this data are items such as the different universities included on the IPT (important if attempting to include a university with specific facilities or resources) average skill levels in various areas, and a suggestion for the IPT leader, based on the leadership scores of each current IPT member. The tool user can add and remove IPT members at will to experiment and find the combination the (s)he most prefers.

Student team leaders had access to the IPT Former tool, which allowed them to, first, select an IPT (such as CAD, seen here), and then experiment with different combinations of team members. As IPT membership is altered, the statistics for the IPT on the far right update to give the team leader an idea of the characteristics of the potential IPT.

Once the user is satisfied with the combination of IPT members and an IPT leader has been selected (bottom-center), the user can hit the “Submit” button to create the IPT. The IPT is

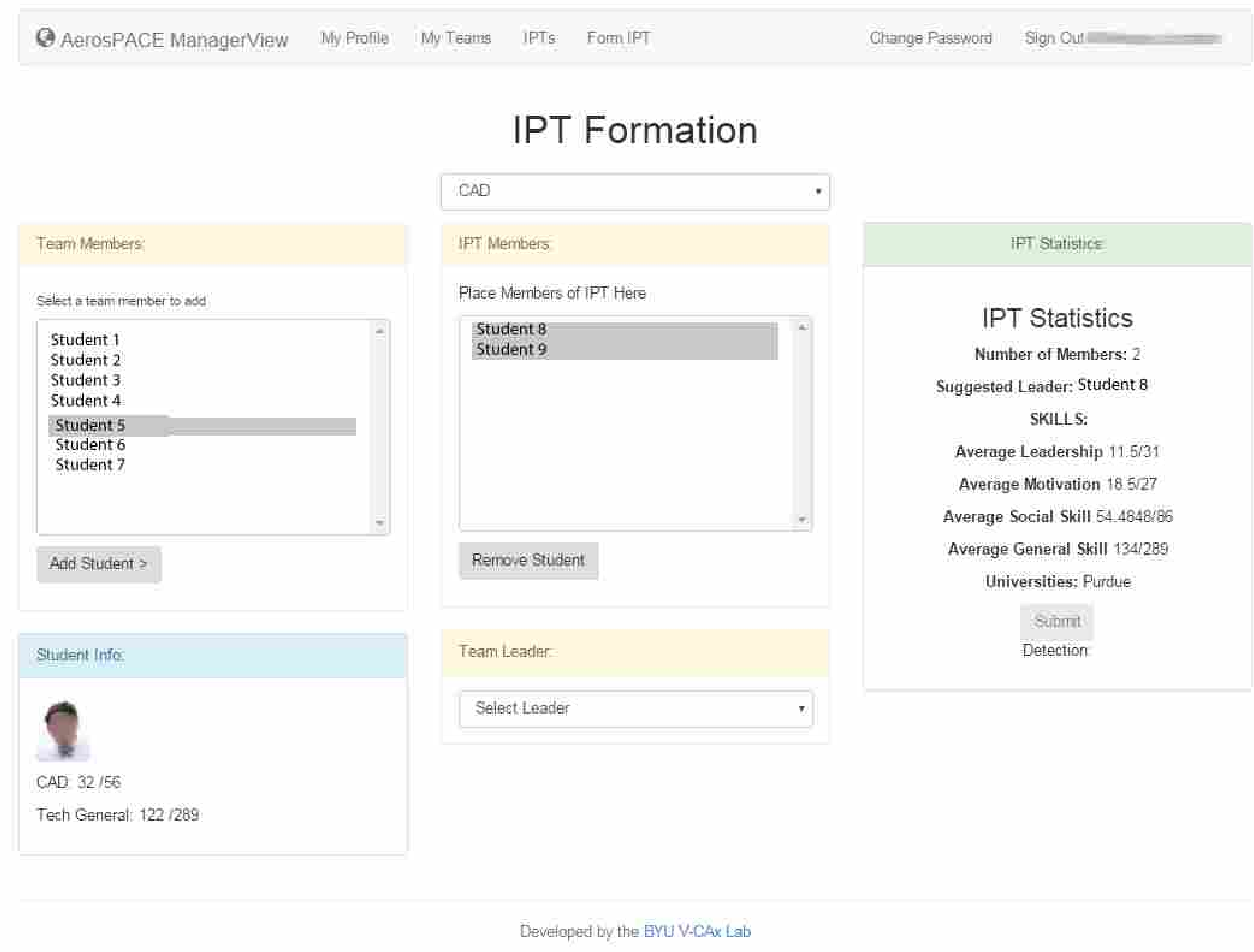


Figure 5.11: Student team leaders had access to the IPT Former tool, which allowed them to, first, select an IPT (such as CAD, seen here), and then experiment with different combinations of team members. As IPT membership is altered, the statistics for the IPT on the far right update to give the team leader an idea of the characteristics of the potential IPT.

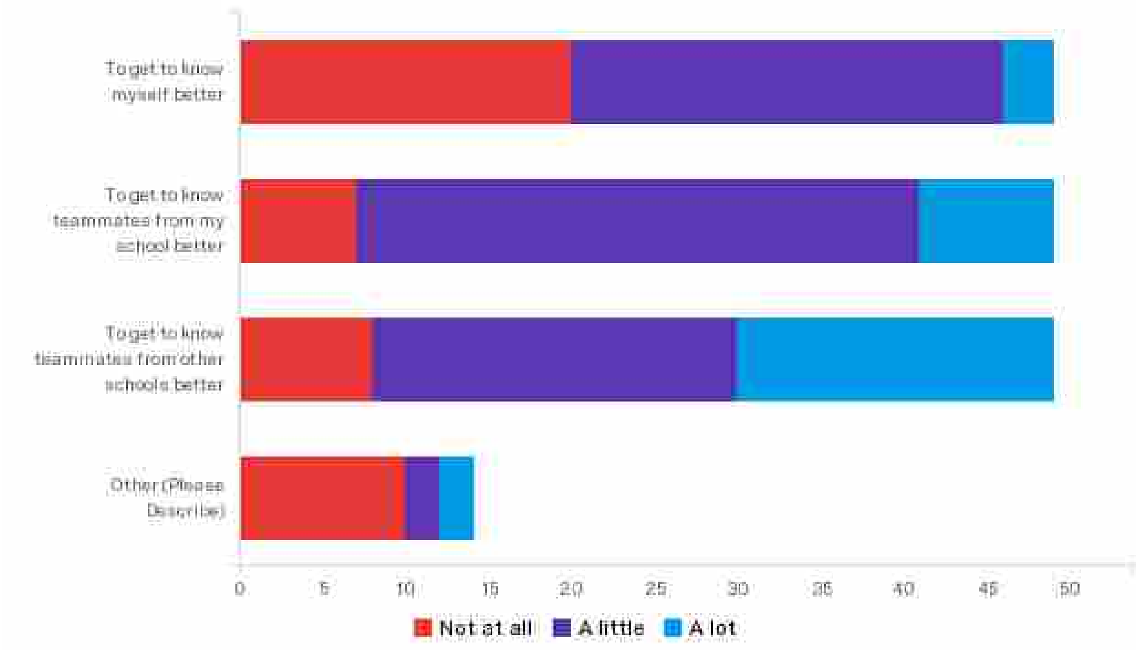


Figure 5.12: Personal use of profile system by students

then visible to all team members, along with other formed IPTs on their team when they click the "IPTs" link at the top of their system window.

System Use and Feedback

As part of a survey administered to AerosPACE students about half way through the first semester of the project, students were asked about their use of the profile and team formation system. Of the 69 students who responded to the survey, over 70 percent of students had accessed the system at least once, and more than 50 percent had accessed it two or more times. When asked what they personally used the information available on the system for, students indicated that one of the most common uses of the system was to get to know teammates from other schools better (see Figure 5.12).

Teams used the system collectively as well. As can be seen in Figure 5.13, the most common uses of the system by teams were to decide who would be part of each IPT and who would be IPT leaders.

Observation confirmed teams' use of the system. In one interesting situation, students on Team VIPR were very eager to use the information in team members' profiles. While the IPT

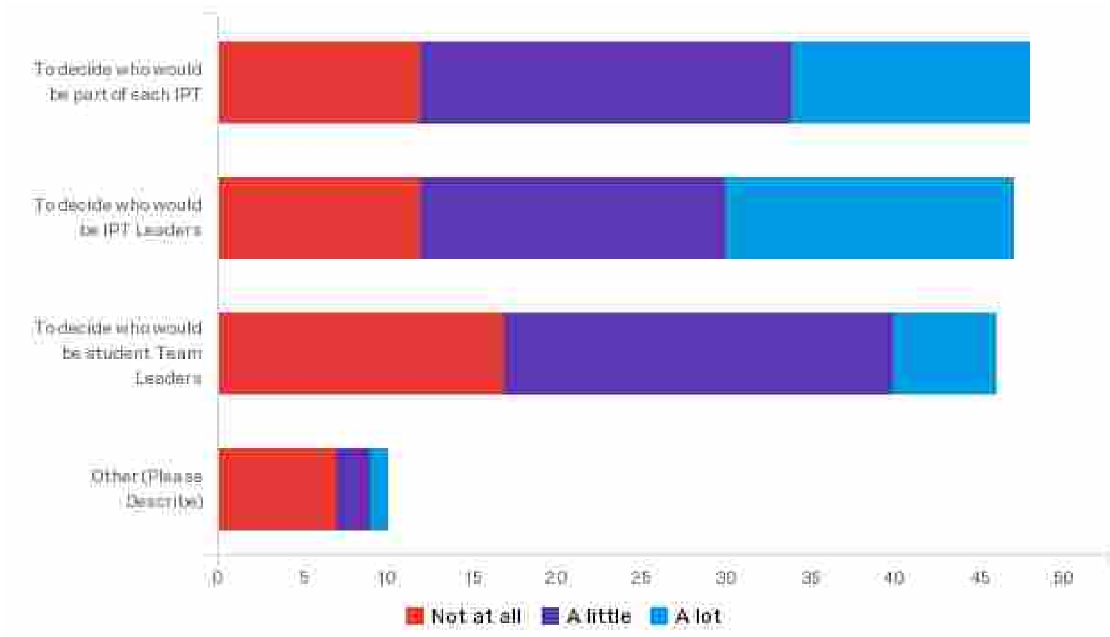


Figure 5.13: Teams' use of the profile and team formation system

Former tool was being fine-tuned for use by the AerosPACE teams, members of Team VIPR, seeing that some of each teammate's profile was kept private from other team members, decided to share all their "personal" information from their profiles with their teammates. Once they had entered it into a spreadsheet, they began manually doing what the IPT Former tool semi-automates, going through various combinations of IPT members to attempt to optimize the combinations. This team clearly recognized the power of a shared mental model of the team and were eager to have it.

Admittedly, an argument could be made that, by using the profile system for such purposes as "getting to know teammates from other school better" that they were reducing process losses instead of maximizing potential productivity. Specifically, getting to know one's teammates better may help establish trust and mitigate ability process losses, such as evaluation apprehension or ability to recognize and exploit teammate expertise [16, 22, 125]. While this is certainly a desirable benefit that should not be ignored, the purpose for providing this functionality was to improve the formation of the IPTs, and is thus primarily classified as a productivity maximizing tool.

As well, students offered suggestions for improving the system. More than one student suggested promoting the system more and making the system more accessible, or part of one of the other online tools used in the AerosPACE program, such as MS Sharepoint. Requests for more detailed information on each student were also common. Students who were not team leaders tended to want access to more detailed information about their peers. One interesting suggestion dealt with how to attempt to control for the fact that individuals may rate themselves differently in the same area despite having similar levels of skill in actuality. For example, one respondent may never rate himself higher than a 6/10 in any technical skill area, while another respondent's self-ratings range from 1 to 8/10. To compensate, this student suggested normalizing a student's scale against his or her highest self-rating. So, the student whose highest self rating is 8/10 has all her ratings adjusted to be slightly higher. The basic problem of course, is the subjectivity of self-ratings.

Advanced Tracking

Ultimately, multiple of the methods suggested by Naikar et al. [59] should be used to provide a more objective view of each individual in a profile and team formation system. Although not implemented in the version of the system used by the AerosPACE 2015-2016 program, we have demonstrated the ability of the system to automatically update individual profiles based on various inputs. These input sources include:

- Data from self/peer/supervisor surveys (via Qualtrics)
- Data from use of a CAD tool (Siemens NX)
- Data from use of MS Excel

The application programming interfaces, or APIs, of these tools allow us to automatically extract data and populate it to the database where individual profile information is stored. Use of tools such as NX and Excel could be recorded as part of a profile-owner's Technical skill (for a particular sub-skill), enabling managers to organize teams based on criteria such as a candidate's hours of experience using NX, or even a candidate's experience using specific features or environments within NX. With NX, we have even been able to instruct the system to only count time a user is actively using the program towards his/her "Hours of NX Experience" Technical Skill sub-area. The possibilities of such a system are discussed further in the Conclusion chapter.

5.6 Highlighted Findings from the Modeling Competition

An important finding regarding measurement of different skills that can be recorded as part of the profiles of members of engineering design teams emerged from the MU modeling competition described in the background chapter. As part of the competition, participants were asked to complete the full Purdue Visualization of Rotations Test (PSVT:R). It was expected that teams with higher average scores for the PSVT:R test would perform at a higher level than those with low PSVT:R results. However, this hypothesis was not supported. No significant correlation could be found in the data from the competition. We did find, though, that a larger variance of PSVT:R scores within a team had a strong, nearly statistically significant negative correlation with team score. Standard deviation of intra-team PSVT:R scores was calculated using the three team members' PSVT:R test scores, and ranged from 0.5 to 8.06. Standard deviation in a given team's PSVT:R test scores actually proved to be the largest factor in predicting a team's score.

A linear regression of team score vs. standard deviation of team PSVT:R score can be seen in figure 5.14. The regression,

$$Score = 2.636 - 0.153 SD_{PSVT:R} \tag{5.4}$$

where, *Score* is the team's competition score and $SD_{PSVT:R}$ is the team's standard deviation of PSVT:R scores has an R^2 value of 0.195 (p = 0.076).

Another method of analyzing this data, the partitioning method (Decision Tree model) in the statistical software JMP, was also used. The partitioning method exhaustively searches all possible groupings or "partitions" of the data set [126]. By recursively grouping the data to form a decision tree until the desired fit is reached, the factors most related to the desired output variable (a team's score, in our case) can be identified. This platform was run with all measured factors (see Table 5.9).

With these parameters, partitioning showed that the largest factor in predicting team score was the Standard Deviation of intra-team PSVT:R scores. Those teams whose standard deviation was less than three had a mean score of 2.60 (out of 4.00), while those teams with a higher standard deviation than three had a mean score of 1.58 (out of 4.00). This may indicate that, of more importance than having one or more highly skilled modelers on a team is having team members

Table 5.9: Factors included in partitioning analysis

Measured Factor	Method of Measurement
Adjusted Scores	Scores given to teams by panel of expert judges adjusted by a handicap due to bugs in the software.
PSVT:R	A participant's score on the Purdue Spatial Visualization Test, administered via the post-competition survey
Standard Deviation	Standard deviation of test scores within a team for the PSVT:R test.
Team Familiarity	Survey question asking team members how well they knew the other two team members (0-4)
Communication	Survey question asking team members how often they talked with their teammates (0-4)
Looking at Screens	Survey question asking how often team members looked at the screens of their teammates (0-4)
Total Communication	A value averaging the communication score and the Looking at Screen scores (0-4)
NX Familiarity	A survey question asking team members how familiar they were with NX (0-4)
NX Familiarity Standard Deviation	The standard deviation in team members' responses to the NX familiarity survey question
Leader	Survey question asking if their team had adesignated leader
Assembly	Survey question asking if their team used an assembly as the modeling technique.
Strategy	Survey question asking if their team had a specific strategy made before modeling
Orientation	Survey question asking if their team designated a specific orientation to follow while modeling

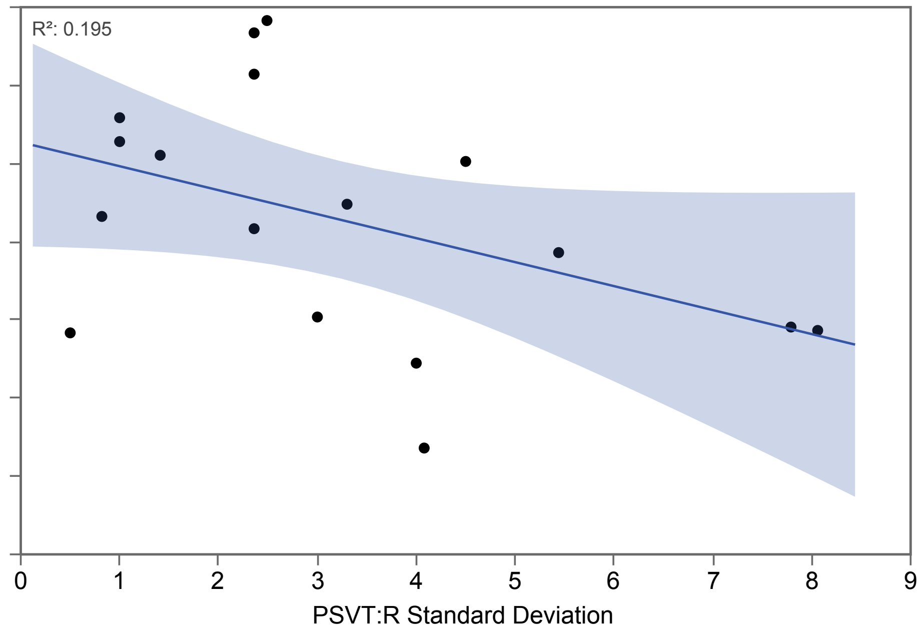


Figure 5.14: A linear regression of team score vs. a team's standard deviation of PSVT:R test scores shows a negative correlation

who are at a similar skill level. This leads us to hypothesize that variance in modeling talent is an important factor in MUCAD team performance. As can be seen in figure 5.15, there was an apparent trend in the competition regarding the amount of variance of a team's PSVT:R score and the team's score in the competition. Future research should further investigate this relationship.

One possible explanation for this result comes from Erickson and Gratton, who explain that the larger the fraction of team members who are strangers on a team, the less likely teammates are to exhibit collaborative behavior [73]. Could it be that teammates feel like "strangers" on a team where the other members are significantly more or less talented than they are? Perhaps teammates with different levels of talent or experience communicate in different ways when attempting to create a shared mental model of the work to be done. Or, perhaps, swift trust is more difficult to establish when one or more members of a team perceive other members as being significantly less (or more) talented than themselves [16]. Morgan et al. found that in at least some cases, dyads of musicians attempting to improvise together were affected by their perceptions of their partner's skill level [127]. Any or all of these potential factors may have been exacerbated by the short time-scale of the competition, since Levi points out that often diversity (including diversity of skill) can take time to come to terms with [9].

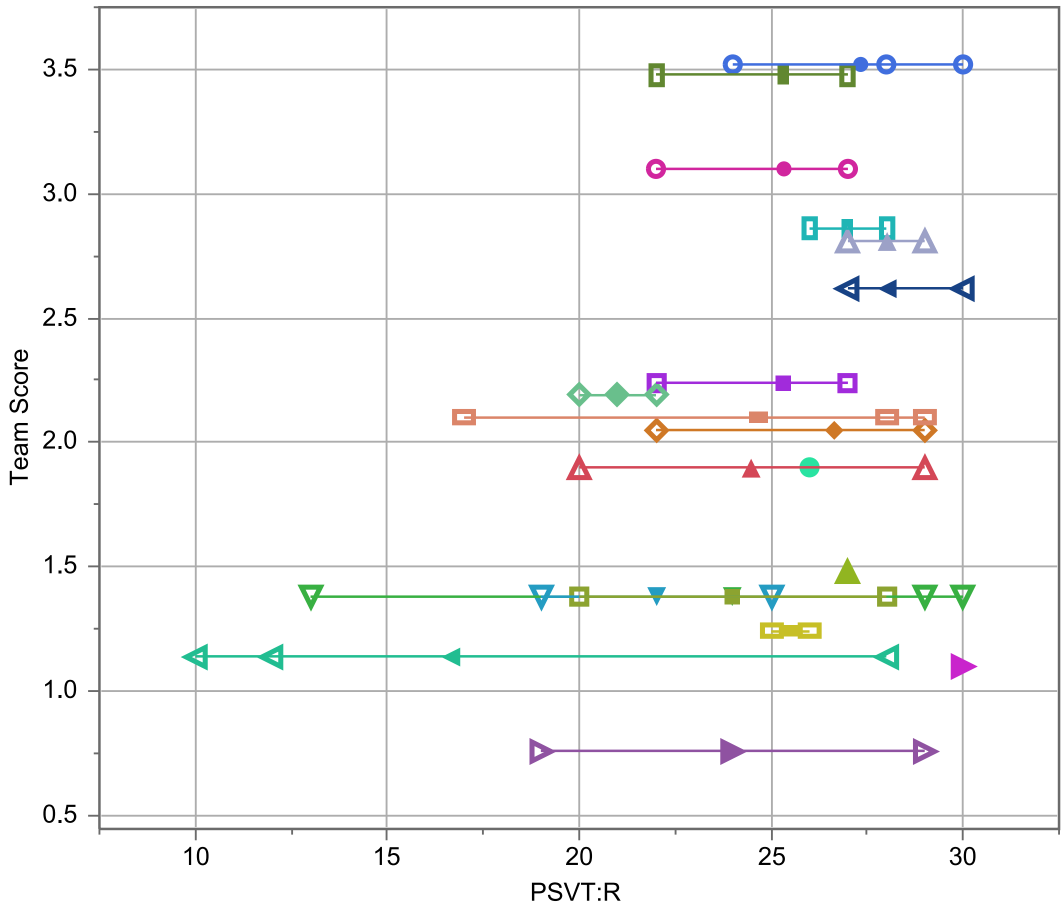


Figure 5.15: Individual (hollow points) and team average (filled points) PSVT:R scores versus Competition Score. Note the general trend of less variation between team member PSVT:R scores as Competition Score increases.

Another related possibility worth looking into in future research is what type of "sport" MUCAD teams are "playing". According to Swaab et al., different sports teams have different reactions to increased levels of talent on the team. In some sports, such as baseball, the relationship between talent level and performance is nearly linear, and team performance never decreases as talent increases. In other sports, such as basketball, there is a definite leveling off and even decrease in performance after talent reaches a certain level [74]. Future research could attempt to determine if teams working in MUCAD are affected by a similar "Too Much Talent Effect".

CHAPTER 6. MINIMIZING PROCESS LOSSES BY IMPLEMENTING EFFECTIVE MULTI-USER STRATEGIES

6.1 Introduction

Once a team has been formed, much of their actual performance has already been determined and cannot be changed without altering the composition of the team. These items that cannot be changed represent the $Prod_p$. However, teams' $Prod_a$ also depends on how well teams are able to minimize $Losses_{pcs}$, or performance losses due to inefficiencies or other failings of the process they are engaged in. As discussed in the background section, process losses originate from many sources, including the strategies and methods used by the teams. This chapter addresses principles and methods that have been derived which help enable teams to minimize these losses and thus maximize their $Prod_a$.

6.2 Team Strategy Lessons Learned from a Multi-User Modeling Competition

6.2.1 A Multi-User Modeling Competition

In the MU modeling competition explained in the Background section, teams of 3 students competed for a set time period (about a half hour) to model a small sheet-rock cutting guard as accurately as they could. The assemblies were then evaluated by experienced judges who assigned scores to each team. Examining the notes of the proctors and the video/audio recordings of each team revealed significant insights into how teams that scored higher than other teams operated. The rankings of each team can be seen in Table 6.1.

As can be seen, scores varied widely from the best to the worst scoring teams in the competition. Two case studies will be examined. One compares the two highest scoring teams in the competition to the two worst scoring teams. The second case study explores an interesting com-

Table 6.1: Teams are shown in order of descending score, with the maximum possible score being 4.00. Note that the scores presented in this table have been adjusted to account for the effect of software bugs experienced by each team (explained in the background section).

Team Label	Adjusted Score	Notes
A	3.41	
B	3.34	
C	3.07	
D	2.79	Student Team
E	2.64	
F	2.55	
G	2.51	
H	2.24	
I	2.16	TA Team
J	2.08	
K	1.93	
L	1.90	
M	1.62	
N	1.54	
O	1.52	
P	1.45	
Q	1.43	
R	1.42	
S	1.22	
T	0.98	
U	0.68	
V	0.60	

parison between a group of teaching assistants for an introductory CAD course who entered the competition as a team and a team of some of their students.

Highest and Lowest Scoring Teams

Figure 6.1 shows the finished models of the top two and bottom two teams. These images serve as a reference to show the differences in the quality and completeness between each team. The two top teams' models are nearly complete. One of them only lacks proper assembly arrangement. The two bottom teams are missing complete components in their final models.

Based on our observations, there were three characteristic differences between the top and bottom teams:

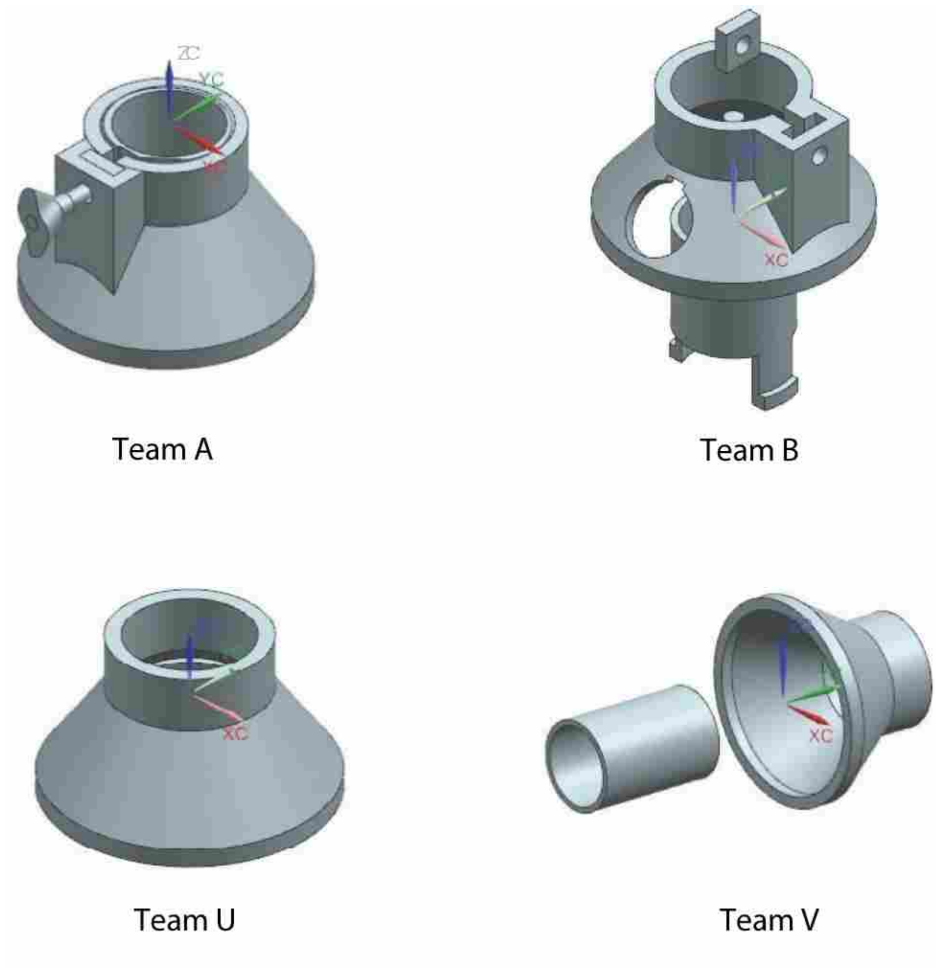


Figure 6.1: The top and bottom teams' models. The winged bolt for Team B and the slide for Team U are partially hidden from view inside the cone.

1. The team leaders in the bottom teams had a negative outlook on the competition and were not the most skilled members of the teams.

2. The top teams had higher quality communication than the bottom teams. "Quality" of communication will be further defined below.

3. The overall strategies of the top two teams were more proactive than those of the bottom two teams.

Although none of the teams unanimously reported having a team leader in survey data, we observed that both of the bottom teams and one of the top teams had "de facto" leaders. Here we define a de facto leader as a team member who took charge of the team by managing strategy and assignments during the competition. Although the de facto leader fulfilled a leadership role, (s)he was not officially identified by his or her teammates as the leader. These de facto leaders were identified during the competition by the proctors. In reviewing the competition video recordings, we confirmed these observations.

Team V had the most apparent de facto leader of all four of these teams. Contrary to our expectations, their leader was unhelpful and had a negative effect on the team. When he encountered problems due to program errors or lack of skill, his responses included hitting the keyboard, uttering expletives and mumbling. Such an attitude from a leader could be detrimental to team performance. It is also interesting to note that he was not the most skilled user on his team. At one point in the competition, the proctor noted that there was "conflict" because the team leader did not know how to use certain features in NX. The most skilled teammate did not know the other two teammates previously, which may have further exacerbated the problem.

Team U also had a less skilled de facto leader who spent the first 19 minutes of the competition creating a single sketch. It is apparent from the video recordings that he considered himself the most skilled because he was most familiar with NX. His teammates, however seemed to fare better because they modeled more quickly. One of them had nearly completed another part when the de facto leader finished his first sketch. Like the leader of the other bottom team, this leader had a negative outlook on the competition. In the post-competition survey he stated that the multi-user software was, "next to useless and mostly a waste of time and money." In contrast, a team member from Team B reported that "seeing others' work means it's easier to spot problems early and have everyone available to fix them." This contrast in opinions indicates that Team B used the multi-user aspect to improve their model while the de facto leader of Team U either ignored these aspects or did not take advantage of them.

On Team B, there was a de facto leader who played a very small role and on Team A, we did not identify one single leader. The leader on Team B communicated very little and when he did, it was mostly to verify dimensions and to make sure that all the teammates were doing alright.

In conclusion, if a team has a leader, in order for him or her to help the team, (s)he must be a leader with a positive outlook and the ability to assist his or her teammates. Leaders who have opposite characteristics will have a negative effect on team performance. Our findings here do not completely reject the idea that leadership matters, but instead suggest that leadership style is what makes the difference.

We also hypothesized that communication would have an effect on team performance in the MUCAD environment. This analysis shows that high quality of communication may matter much more than high quantities of communication (as supported by the analysis in the section *Leadership and Communication*). Here, high quality of communication is defined as promoting a positive attitude and focusing on overcoming the real problems preventing success in the competition.

The video and proctor notes show that the bottom teams' communication was negative or of low quality. Negative communication may have inhibited these teams' abilities. While the top two teams may have communicated less, their communication was positive. Table 6.2 shows examples of communication observed from the four teams.

One interesting note here is that, although we found by examining the video recordings of the sessions after the competition that these four teams experienced a nearly identical number of problems due to software errors, the proctors noticed very few errors experienced by the top teams but did notice the errors experienced by the bottom teams. This is explained at least in part by the quality of the bottom teams' communication. A lot of the bottom teams' communication involved complaining to each other. The top teams' communication involved verifying that things were going well and answering each other's questions. These observations seem to coincide with observations made regarding the case discussed in the section *The TAs vs. The Students*, which will be discussed next.

Overall, the top two teams had a more proactive modeling strategy. As mentioned earlier, the leader of Team U was working on a single sketch for mare than half the competition. For the first couple of minutes, his teammates familiarized themselves with the features and layout of the NX software. They eventually began idly chatting with each other because their leader was taking a long time to finish the first sketch. Not until about 7 minutes into the 25 minute competition time did these two teammates begin to model. Even taking into consideration the fact that these users were unfamiliar with NX, there was no reason for them to make no contribution during the first quarter or more of the competition. In the end, this team lacked entire components of their model.

Team V experienced similar dysfunctional problems. After about 20 minutes, one of the teammates simply quit modeling and started doing homework. The most skilled teammate and the

Table 6.2: Differences between high and low performing teams' communications during the competition

Examples of Communication From the Top Two Teams	Examples of Communication From the Bottom Two Teams
"Make sure to work on the assembly later." (To teammates)	Crying noises, expletives, or hitting the keyboard when unsure how to use software.
"What are the dimensions?" (To teammates)	"Oh my heck. This software sucks!" (while experiencing difficulties attempting to perform modeling task using incorrect method)
"Hey, I made one too many parts... so don't do this one." (to teammates, indicating which one with cursor)	"Oh, heck, I picked the wrong one I think..." (to himself after working on a part for several minutes)
Teammate 1: "Are we going to re-position them all later?" Teammate 2: "Yes, we've got them in an assembly, so we can do that."	Talking about class and other items not related to competition
When software bugs impeding modeling occurred, calmly asked proctor questions until issue was resolved.	"Haha, yeah, we're exploring NX, that's all we're doing right now, but I found something to do..." (In response to question from teammate after several minutes of competition time)
"Hey, what's the button to make the view orthogonal? Oh, thanks." (To teammates)	Not asking teammates specific questions about how to resolve challenges (or waiting for several minutes to ask), but readily expressing frustration about challenges.
Assigned out parts and tasks, and clarified that model would use an assembly within first minute of competition time.	"Are you guys just waiting on me over there? Sorry." (To teammates about seven minutes into competition time)

leader continued to work on their parts, but the proctor notes that they were working "independently", or, in other words, they were not communicating assignments to each other.

In contrast, members of the top two teams employed strategies that utilized every minute of each teammate's time. In both teams, we saw that when a given teammate finished an assignment, he would ask his teammates what more he could do. When a teammate saw a need or sensed that other teammates might have time to take care of that need, he would ask them to take care of it. For example, one member of Team A noticed that the parts needed to be assembled and told his other two teammates to start working on it when they had time. There were also long periods where no talking at all took place.

TA's Vs. Students

Another notable case from the competition is the performance of the teams that finished fourth and ninth in the competition. The fourth place team was composed of three students enrolled in BYU's introductory CAD modeling course at the time of the competition. The ninth place team was composed of three teaching assistants for that same class. As such, they were assumed to be some of the best modelers among their peers and were thought to have a distinct advantage. Here we will refer to these two teams as the "Student Team" and the "TA Team".

The teams' NX familiarity scores, as reported in the post-competition survey, reflect the difference in experience between the two teams. The TA Team had a familiarity score of 3.67 out of 4.00 and the Student Team had scored 3.00 out of 4.00. Based on this one would have expected the TA Team to perform better than the Student Team, but surprisingly, this was not the case. The Student Team received a competition score of 2.79 out of 4.00 while the TA Team's score was 2.16 out of 4.00.

Comparing the communication patterns of the two teams is instructive as to what helped the Student Team to perform better even though they were less experienced. The proctors noted that the Student Team was more likely to communicate when they were struggling. The TA Team members were less willing to let their teammates know when they faced problems. In fact, one TA Team member spent several minutes struggling to model the main outer guard (his assigned part) before telling his teammates about his need for help. After 13 minutes (over half the competition duration), he finally admitted that software errors were keeping him from modeling the part effectively. He restarted the software and continued to work on the model while the proctor noted that another teammate was "looking for something to do." After further problems, he asked another teammate to model the part. With only about nine minutes left, this other teammate was also unsuccessful. Their final submission, which is seen in Figure 6.2, was missing this outer guard which drastically reduced their final score. As has been previously discussed, the team scores were nor-

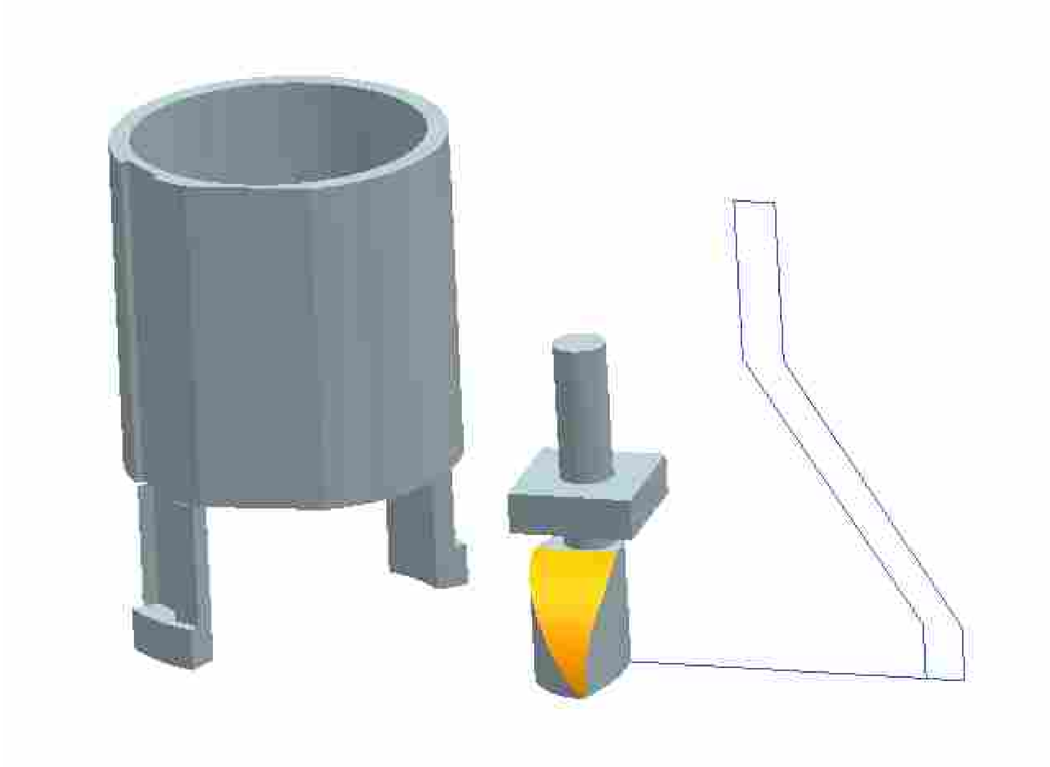


Figure 6.2: Final result of the TA Team's modeling efforts; the profile sketch is the only part of the outer guard which they completed

malized to account for the frequency and severity of software errors such as the ones encountered by this team, allowing us to analyze team interactions as if no errors had occurred.

The Student Team faced similar software challenges but handled them in a more collaborative manner. One teammate had trouble modeling the exact same part as the TA Team member mentioned above. However, in this case, a proactive teammate stepped in to help model. This helper would, over the course of the competition, become the de facto team leader by helping others, providing guidance, and checking up on team members. As a result of this collaboration, the Student Team completed the main outer guard and scored higher than the TA Team. The Student Team's final submission is shown in Figure 6.3.

Based on these observations, it appears that teams with members who are more forthright about major problems they encounter perform better than teams which are less inclined to do so. It is also, as noted in the section *Leadership and Communication*, important for teams to have a helpful leader who can effectively address those problems. When a team is not as good at

Figure 6.3: Final result of the Student Team's modeling efforts

communicating issues as they arise, their performance is likely to suffer, even if they are more familiar with the software.

Aside from proctor observation, the communication differences between these two teams are evident in their responses to the post competition survey. Their answers to the question "How often did you look at your teammates' screen(s)?" are especially instructive. Only two members of the Student Team responded to the survey, while all three members of the TA Team responded. Even with a missing response, the highest frequency reported from each team can be used to compare their communication patterns. The two teammates on the Student Team reported looking at their teammates' screens once every five minutes and one time or less during the competition. Two TA Team members reported frequencies of two or three times during the competition while the other team member reported one time or less during the competition. Thus, the Student Team had at least one team member who was more proactive at communicating in this way than the TA Team.

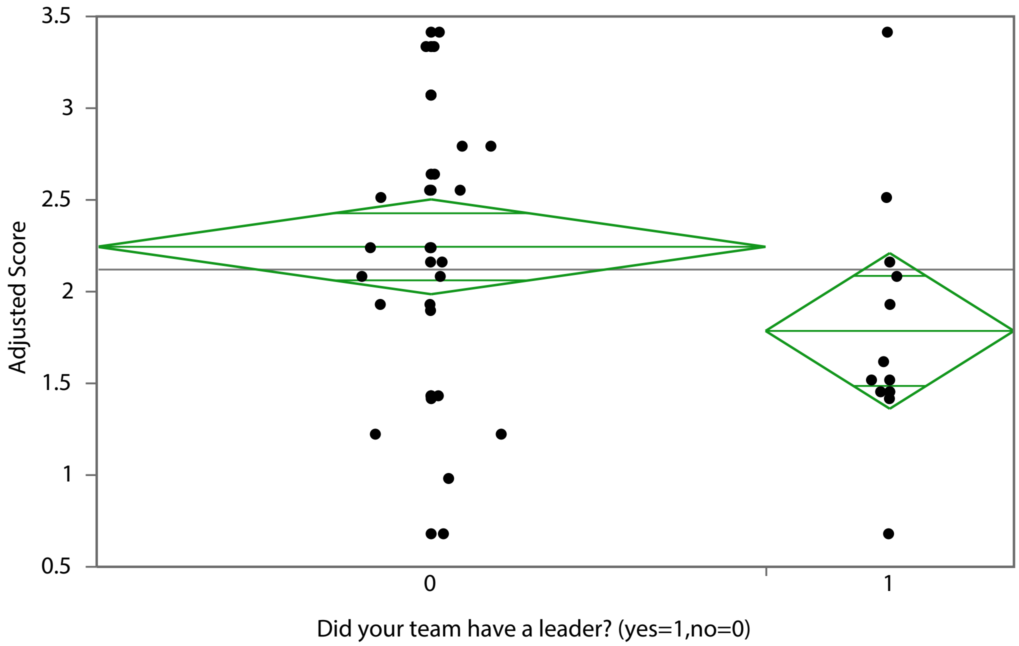
Leadership and Communication

Leadership is widely considered to be an important factor in team performance [77, 78]. It was expected that teams with leaders would score more highly than teams without leaders. However, data from the modeling competition shows evidence that seems to contradict this theory. Rather than showing a positive correlation between performance and having a leader, teams that had no leader actually scored higher than teams that did, as shown in Figure 6.4. However, it is important to note that, based on the survey responses, for some teams there was some discrepancy as to whether or not the team had a leader. As a source of future work, a larger sample size could be taken to further validate the statistical significance of these results.

This finding led to the investigation of how the team dynamics present in the modeling competition could cause a departure from the results we expected. From the literature, communication has consistently appeared as an essential element for project success in engineering teams [65]. Based on existing literature and a qualitative analysis of the modeling competition results, we propose that team success will be greatest when the leader fulfills a role of increasing productive types of communication and decreasing detrimental types of communication.

We define productive types of communication as those that facilitate the teamwork process and allow for successful completion of the project. This can include discussing expectations, setting goals, and dividing the work between team members. Reflecting on team processes in order to improve them is another type of productive communication [76]. Productive communication will create a supportive climate that encourages expression of different ideas and opinions. On the other hand, detrimental communication types include blaming and discouraging, which create a negative climate [9]. We include complaining, distracting the team from the current task, and over-analyzing project details as other types of detrimental communication.

Several sources show that communication is most effective when it is used to form a common mental model among team members [11, 51]. According to Macmillan et al., large quantities of communication can be detrimental to team performance, as discussed earlier when comparing



1-0

t Test

Assuming unequal variances

Difference	-0.45859	t Ratio	-2.01517
Std Err Dif	0.22757	DF	25.47419
Upper CL Dif	0.00966	Prob > |t|	0.0546
Lower CL Dif	-0.92683	Prob > t	0.9727
Confidence	0.95	Prob < t	0.0273 *

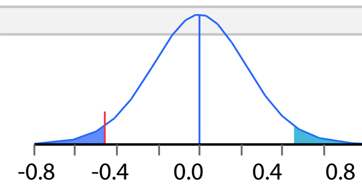


Figure 6.4: Teams with leaders did not score higher than teams without leaders

the top two performing teams against the bottom two performing teams. However, when team members must develop a new mental model or modify an existing one, they need to be encouraged to speak up and express observations, questions, and concerns. This initial communication facilitates building shared experiences and gaining confidence in new technology or other changes. If the leader does not perform the role of promoting this productive communication, team performance will be negatively affected [79].

Macmillan et al. adds that communication is necessary to build an understanding of team members' needs, responsibilities, and expected actions. According to Edmondson, this is especially important in action teams, in which team members must work together in uncertain, fast-paced situations [79]. In the modeling competition, these conditions were present as participants worked to create a model that they had not seen previously in a limited amount of time. In order to be successful, teams needed to build a mental model of the cutting guard as well as a mental model of how their team should function in the context of using the MUCAD software, something most teams found new.

Some case studies from the modeling competition show examples of how team leaders either promoted or impeded productive communication. In one of the lowest-performing teams, proctors noted that the team member who acted as the leader expressed anger and frustration, which seemed to deter productive communication with other team members. On the other hand, productive communication was common in the highest-scoring team, where team members gave feedback on their progress and what still needed to be done.

The information gained from the literature combined with the data from the modeling competition leads us to a new hypothesis: that it would be expected to see a successful team have a large communication spike at the beginning of the competition time as they build their shared mental model, minimal communication during most of the remaining time, and then a small communication spike at the end when the team members verify what has been done and finalize the model. Of course, the communication must not only be of the right amount and at the right times, but must also be a productive type of communication in order to be effective.

In order to confirm this hypothesis, the audio recordings of conversation between team members for several teams was analyzed. As seen in Figure 6.5, one of the highest performing teams exhibits this expected audio pattern. In contrast, Figure 6.6 shows how a low-performing team has communication scattered throughout the competition time. In listening to the audio from this team, it is clear that they did not have a sufficient shared mental model, as they continued to discuss dimensions and how to complete the model as a team after their initial discussion at the beginning of the competition time.

Based on these findings, we concluded that team performance is not enhanced by having a team leader, but only when that leader fulfills the role of promoting positive communication within the team. If the leader does not fulfill this role, the team's performance may be significantly worse than that of teams with no leader. We also show that there are differences in communication patterns between high-performing and low-performing teams.

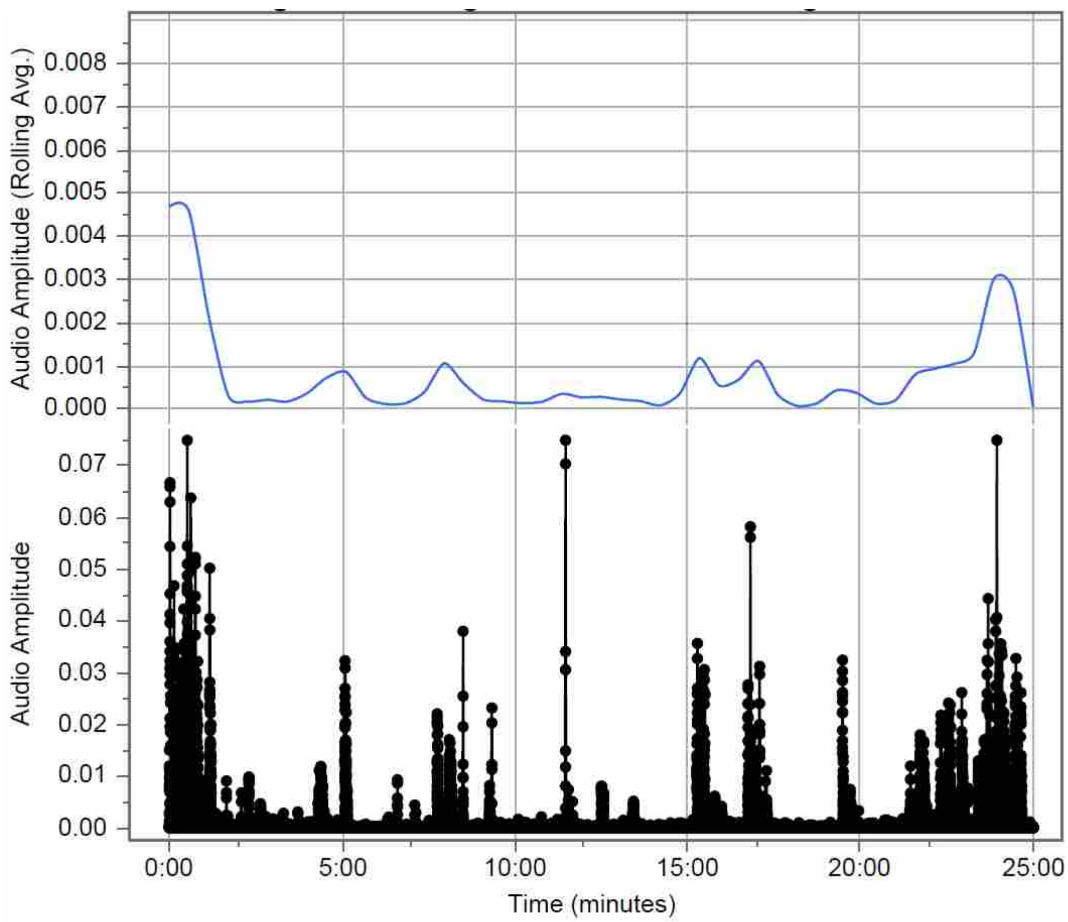


Figure 6.5: Profile of a high performing team's audio activity during the competition

6.3 A Model for Distributed Engineering Design Team Collaboration Tool Use

6.3.1 Introduction

The AerosPACE program also provided a valuable setting in which to study strategies and factors that affect design team performance. While the MU Modeling Competition provided a valuable setting in which subjects used beta MU modeling software and dealt with the stress of a competition and evaluation, it also had some inherent drawbacks. It was short-term, collocated, and involved modeling, rather than design. AerosPACE, on the other hand, while its students only used MUCAD part of the time, provided a setting that involved subjects in a longer term (months instead of a half-hour), geographically dispersed, design (instead of just modeling) project. By studying both situations, a more complete understanding of how to enhance the performance of virtual engineering design teams using MU tools can be gained.

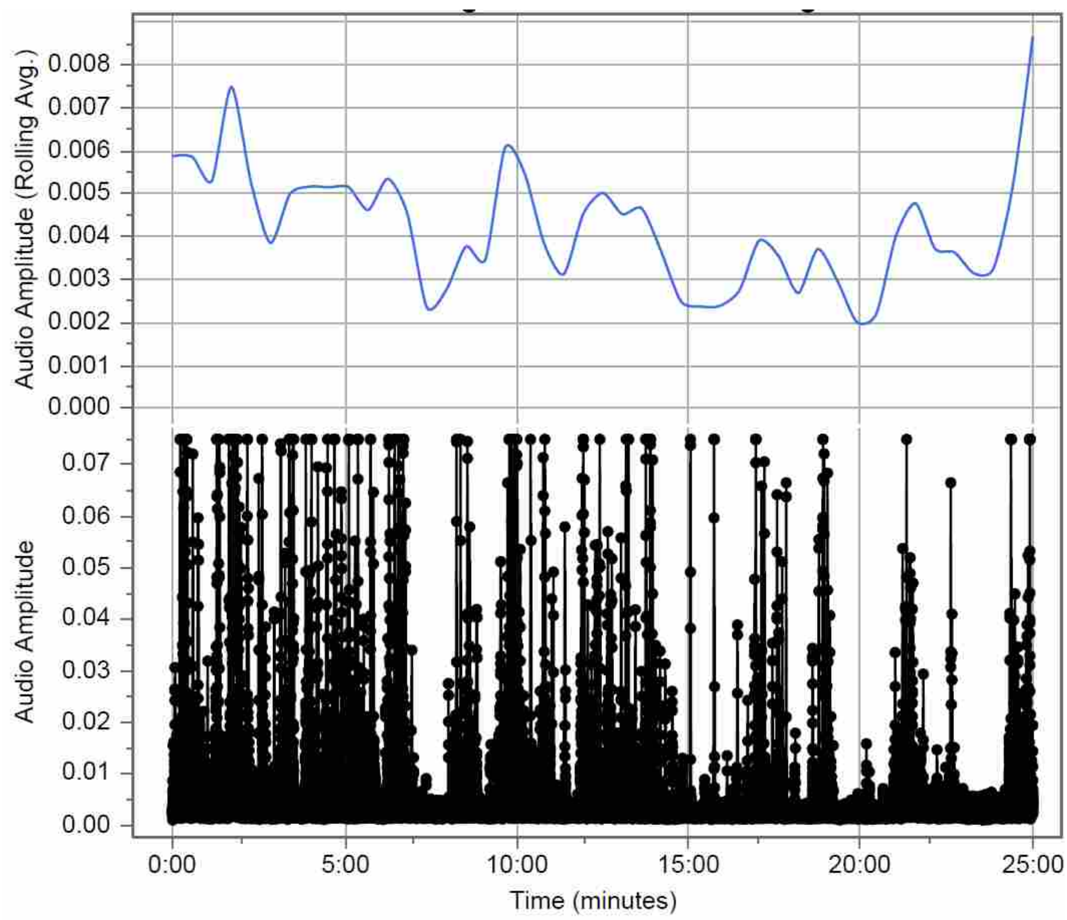


Figure 6.6: Profile of a low performing team's audio activity during the competition. Note the generally increased level of audio activity.

After observing and studying the AerosPACE program in depth for more three years, a model of collaboration for virtual design engineering teams was developed. This model explains recommends tools and methods virtual engineering design teams should consider at each phase of the product development process in order to work more successfully. Examples from the AerosPACE program are reinforced with findings from the literature.

6.3.2 Data Gathering

Multiple methods of gathering data regarding tool use and experiences among AerosPACE students were used. These methods included internet-based surveys, in-person and phone interviews, and observation of students and teams, both in person and in virtual team settings. Students agreed via Institutional Review Board consent forms to be research subjects.

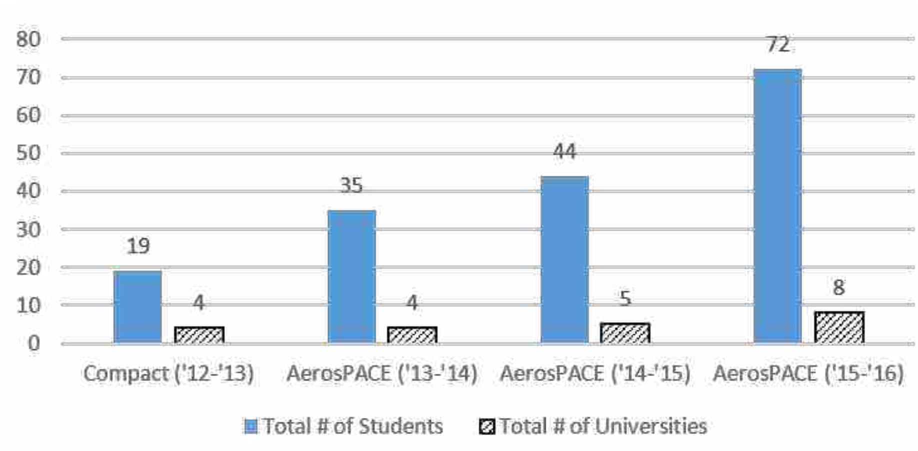


Figure 6.7: Growth of the AerosPACE program over time

Over the course of the AerosPACE program, we have observed student teams as they have worked from various institutions to design, build, and finally fly their UASs. Approximately 170 students have participated in the program since 2012 from 10 different institutions (see Figure 6.7). Besides observation, we have also performed in person and phone interviews and approximately four internet based surveys per year. These surveys and interviews served various research purposes, but also provided insights into the communication needs and preferences of the participants as individuals and teams. We were also able to study the feedback given to the students by the industry professionals and faculty coaches who evaluated their presentations and progress in regular design reviews.

6.3.3 Proposed Model of Collaboration

A typical product development process, adapted from Dieter and Schmidt, includes the following stages:

1. Mission Definition
2. Concept Generation
3. Concept Evaluation
4. Product Architecture Development / Task Mental Model

5. Configuration Design / IPT Design

6. Detail Design

7. Early Full Prototyping

8. Testing

9. Final Manufacturing

[128]. NASA has also developed a toolbox with their own suggested workflow:

1. Conceptual Trade Studies

2. Concept Definition

3. Design and Development

4. Fabrication, Integration, Test, and Evaluation

5. Operations

[129]. These two given processes are similar in stepping through concept generation, design, and then fabrication or manufacturing. The NASA model does differ in that it specifies an operations section when the product is actually put to use. We combine and generalize these two processes for the purposes of this investigation into three basic phases: Early, Middle, and Late.

We propose, based on the literature and our own experience, that in each of these phases, different communication tools should figure more prominently into the team's communications, and that using the right tools correctly at the right time will enhance team collaboration and performance. We outline this proposition in the sections below.

Early Stages

The early stages of the product development process include Mission Definition, Concept Generation, and Concept Evaluation. This section is characterized by the formation of a team, being presented with and learning about the design challenge, and the cyclical generation and evaluation of a large number of ideas.

In these early stages, teams must collaborate and communicate in an environment with initially high amounts of ambiguity. This presents some problems since teams during the early stages need to negotiate design choices and iterate through several designs [65]. Maruping and Agarwal suggest a solution by stating that in situations where convergence of understanding is desired, communication tools that enable "high immediacy of feedback and low parallelism," are best [80]. "Immediacy of feedback" in this case, refers to what we have classified as "Time to Response". Within the early stages of concept generation, therefore, teams should emphasize use of communication mediums that are high in Media Richness, utilize multiple Symbol Types, have low Time to Response, and low Parallelism. During this stage, Permanency can also be low since a large number of ideas, most of which will eventually be discarded, need to be generated and considered [128]. This will allow for less storage of un-needed information.

While there are specific tools that meet the criteria of low immediacy of feedback, low parallelism, and high media richness, we have learned in our experience with AerosPACE that whenever possible, in-person meetings, such as a program kickoff, are key in the early stages. In the 2013-2014 AerosPACE program, no in-person kickoff meeting was held, but students did meet each other in person at the final "fly-off" event at the end of the academic year. In interviews at the end of the year, students indicated that, after finally getting to meet their teammates in person at the fly-off, they felt that many of the issues or problems they faced throughout the year could have been minimized or eliminated if they could have met in person at the beginning of the year in some sort of kickoff meeting.

For example, one student, when asked in an interview whether he felt a kickoff meeting would have helped with some of the interpersonal challenges their team faced, said,

> "I really think it would. I think once you establish a person with a voice and with a face, you actually get to know everyone a little better and kind of where everyone's coming from. There's a personal aspect to it that I think would help to alleviate some issues with trying to discuss things, especially early on when you're forced to make some of these design choices that are going to affect your whole vehicle program moving forward. Really being in sync with one another during that process would definitely make it easier."

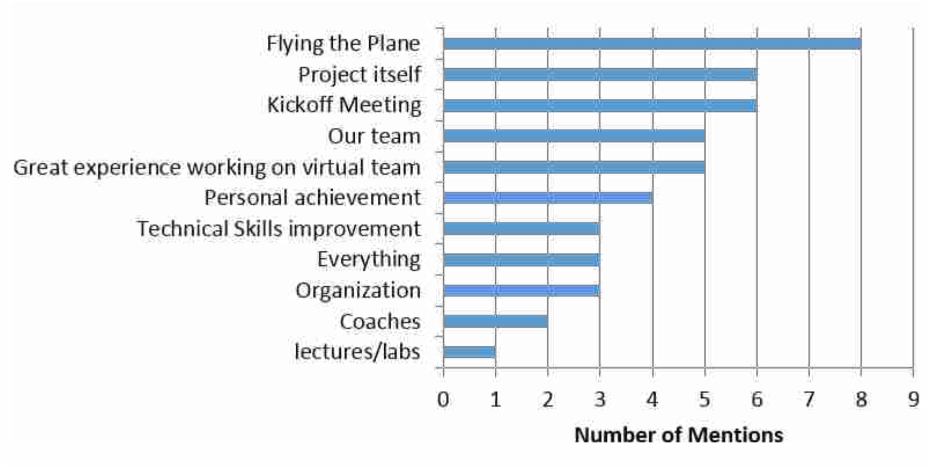


Figure 6.8: The kick-off meeting tied for the second most frequently mentioned item when asked what went well in the program during 2014-2015 AerosPACE program.

At the beginning of the following year's program (2014-2015), a kick-off meeting was held, at which all students from all teams met in one location and spent time together with their teammates. They brainstormed, conducted team-building activities, began work on responding to the program Request for Proposals (RFP), and socialized during a pizza dinner and unstructured time. At the end of the year, when asked what portions of the AerosPACE program they felt had gone well, the second most mentioned item, tied with "the project itself", was "the kickoff meeting". In the survey, students offered comments such as, "the kickoff event was very important for the health of the team throughout the semester," and "The Kick Off meeting was a good start to the program." Figure 6.8 shows the frequency of different items students mentioned in the final survey when asked what things went well during the 2014-2015 AerosPACE program.

Other researchers agree. Siebdrat et al. for example, stress the importance of a kick-off meeting to help virtual teams develop a shared understanding of the project and encourage social cohesion within a team [130]. This shared understanding, including learning who on the team is good at what, is often referred to as a shared mental model and is critical in the formation of a team, [13]. Lovelace et al. have stated that one reason that dispersed teams struggle with forming a shared mental model, is that compared to co-located teams, virtual teams are less likely in the early stages of development to have developed the norms of openness and debate required for task conflict to be effective [131]. Furthermore, Hertel et al. cite a long list of scholarly work on virtual teams, suggesting that a kickoff meeting is an important factor for virtual team success [114].

Hackman also agrees that even well-structured virtual teams need to have everyone physically present for a launch meeting [47].

Once the project commences and in-person meetings are no longer feasible, video conferencing is the next most critical form of communication as it is the form of virtual communication with the highest media richness after face-to-face meetings. It also has a very low Time to Response, low Parallelism, and low Permanence. As Koster et al. point out, most students have been trained to work on local teams [65], so using the tools most similar to in-person communication (such as video conferencing) can help to ease the transition to a fully virtual team environment. Furthermore, in the absence of in-person communication, high quality video conferencing can enable participants to develop trust and cohesion through a richer interaction than other virtual tools [9].

Teleconferencing and web conferencing are also viable options, but should be deferred to video conferencing in the initial stages as the level of media richness is lower in both cases. As ideas begin to form and preliminary designs are being made, a gradual transition to web conferencing can be made to facilitate exchange of more technical data and symbol types. Images, 3D models, and presentations of certain ideas can then be viewed and discussed with all parties able to see the proposed ideas.

As mentioned before, although tools such as video and web conferencing offer some of the highest levels of media richness and other characteristics desirable for this stage, they also have some of the lowest levels of Accessibility. Levi and our experience with AerosPACE emphasize the need to learn how to use these tools effectively. In the AerosPACE program, we have experienced the importance of even the simplest of skills that affect accessibility with regards to tools like web conferencing or video conferencing. One student, interviewed during the 2013-2014 program, stated that he had participated in several web-conference meetings where he could only hear about 30 percent of the conversation because those speaking were sitting too far away from the microphone to be heard clearly. Levi describes a slightly higher order skill that we have also found useful: meeting leaders can request verbal confirmation from specific participants or “reflect” a message to confirm correct receipt of a message [9].

Another important need in the early and middle stages of a design project is the ability of a team to communicate ideas visually. Yang found a statistically significant outcome between the quantity of sketched ideas in the early stages of a product development process and the quality of the design outcome [132]. Chandrasegaran et al. note agree with Kopp that while sketching is important throughout the design process, its impact is felt most during the early, conceptual stages [95, 133]. The ability to communicate ideas using a visual symbol type (sketching) is also considered important by companies in the aerospace and defense industry, according to a survey conducted by Lang et al. [134]. This need led to the development of a shared virtual annotation and drawing tool called the Telestrator, which enables multiple users to simultaneously contribute to a shared drawing space. Its development and use will be discussed in the next chapter.

Recommended tools for early stages

In summary, for the early stages of a virtual team similar to AerosPACE, we recommend that extra consideration be given to the following communication tools, based on our experience and the literature reviewed:

- Face to Face Meetings
- Video Conferencing
- Web Conferencing
- Shared Virtual Annotation and Drawing Tools

Middle Stages

As team members understand the task that needs to be accomplished by the whole team, they begin to narrow the design and select a specific concept, ending the concept generation and evaluation stage. The middle stages, which span Product Architecture Development, Configuration Design, and Detail Design, are characterized by beginning to work in earnest in specific integrated product teams (IPTs), prototyping sub-systems, and completing the detail design (adapted from Dieter & Schmidt, [128]). The work becomes more technical and detail oriented. With the conclusion of the detailed design, team members coordinate the integration of their portion of the product and work together to make sure they interface correctly. Detailed design brings individual portions of the design together, most system-level decisions are finalized, and a decision is made by team management to release the design for production [128, 135].

In these middle stages, we have observed in AerosPACE how both the nature of the design challenge and the teams themselves are different than in the early stages. Details regarding specific sub-systems requirements and components are more plentiful, and the team, instead of working mostly as one large group, begins to work and communicate in two different general areas: the first is intra-IPT work and communication, and the second is work and communication between IPTs at the team level, or "systems integration". IPTs, as smaller groups within the team, are focused on a specific area such as the electronics controls system or the structure of the frame, etc.

Assuming that sufficient levels of trust among team members were established during the early stages of the project, some forms of communication that were highly useful in the early stages may be significantly less necessary during the middle stages of the project. Researchers such as Golden & Raghuram and Doerry et al. found that once trust is high, mediums with high richness (such as face-to-face or video conferencing) are less necessary. Less expensive or more convenient mediums (in terms of bandwidth, Accessibility, Time to Response, and Symbol Type) can be used more effectively and often in this stage once trust is established [25, 136].

As we have observed AerosPACE teams attempt to balance specialized collaboration in small groups with the holistic collaboration at the systems integration level, we have found that regular meetings with all teammates virtually present through a communication medium with a minimum level of richness are essential. These meetings should include all members of the team and allow for each team member to report their progress, talk about any problems, review the project timeline, and integrate their components with the components of other team members. As noticed in AerosPACE, when teams fail to meet on a regular basis the team suffers. In one instance, team members from the same university were unable to attend the regularly held team meetings and so began meeting multiple times a week on their own. Over time, this group began making decisions without the input or consent of their teammates at other universities. This obviously caused some tension in the relationship and caused some members of the team to feel left out and unimportant. "You need to be constantly in-touch with each other to be able to participate," said one student who was left out of the decision making process. It is thus important that teams communicate between IPTs and universities often and regularly. In the AerosPACE program, some teams have communicated by using Groupme, Slack, Google hangouts, or other such readily available software on a daily basis; by doing so they were able to increase their productivity and minimize the integration losses.

Other researchers have come to similar conclusions [65]. Maznevski and Chudoba, in an industry study, found that effective virtual teams follow a temporal rhythm of communicating using tools of higher and lower media richness [82]. The successful teams they monitored would meet either in person or using rich mediums at regular intervals between longer periods of using lower richness mediums. Although on a completely different scale, the pattern they describe is not dissimilar to the one observed in the modeling competition (see Figure 6.5).

In order to span the times between these media rich meetings, we have found that it becomes very important in the middle stages to appropriately utilize collaboration tools with high permanence/durability. Given the level of detail and number of decisions the team makes in the middle stages, it becomes important that discussions and decisions be automatically documented in a manner that facilitates revisiting the reasoning behind them later. The importance of being able to easily capture design rational has been highlighted by researchers such as Bracewell et al. [137] and Klein [138]. Hepworth et al. found that virtual teams that use a shared list of tasks that all members can access and edit simultaneously are able to reduce confusion and increase performance compared to virtual teams without such a tool [72].

For these reasons, all team member should be made familiar with tools such as a shared database like Google Drive, MS Sharepoint, or other similar cloud storage systems early in the middle stages. Hackman, in his classic normative model of group effectiveness, states that an information system is critical to the group's ability to plan and execute a performance strategy [46]. The permanency of a shared database allows team members to reference designs and easily see the progress and work of others. As changes are made and design aspects updated, a shared database reduces the amount of confusion, as there is a common reference point for all to see. Furthermore, these tools not only provide permanence, but also broad symbol variety.

In the AerosPACE program, we have explored different options for such an online tool. During the 2013-2014 and 2014-2015 program years, students expressed dissatisfaction with the chosen tool, in large part because of the tool's poor file organization capabilities. In surveys and interviews, students expressed the desire to use a tool such as Google Drive, which would allow them to organize, share, and search files as they wished. However, because of security protocol,

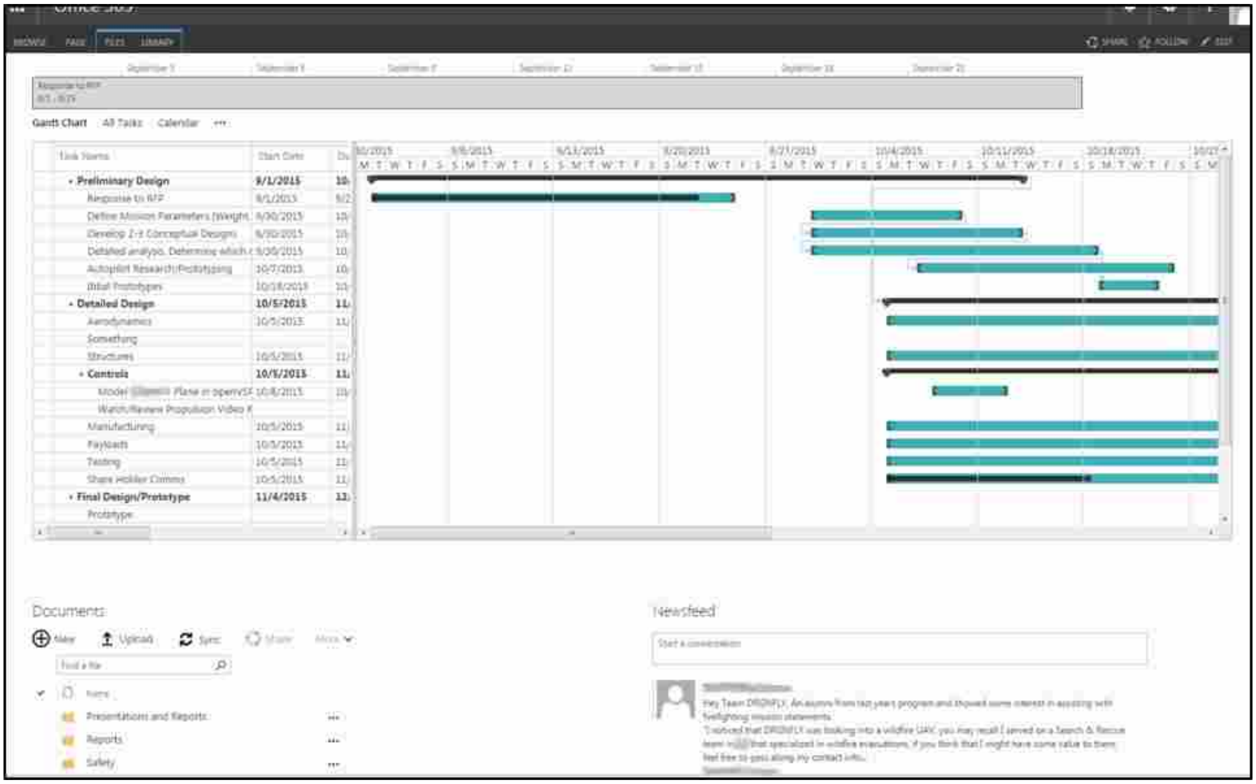


Figure 6.9: A screenshot of the team page for one of the teams from the most current (2015-2016) AerosPACE project showing the Gantt chart, file-folder organization system, and team discussion thread on their main page.

access to Google Drive was restricted for team coaches from the Boeing Company. To remedy this situation MS Sharepoint, which can be federated via security protocols, was implemented, allowing teams to create and share items such as Gantt Charts and task lists as well as organizing files and folders on a website with sub-pages that each team manages themselves. An example of one team's use of the system can be seen in Figure 6.9. This screen-shot shows how any team member can, in one central location, access schedule information, find files which are organized the way their team chooses to organize them, and view the latest information posted by teammates and faculty on the Newsfeed. Other apps can be added or removed as the team chooses. Students, faculty coaches, and sponsor coaches all have access to the tool.

During interviews in the 2014-2015 program year, we also found that during the middle stages, Time to Response was often important to students in deciding which tools to use. In the middle stages, the work the team is performing is often relatively technically complex. As well, scheduling challenges imposed by working across time zones and varied university and individual student schedules adds to the difficulty of communicating simultaneously. For these reasons, students indicated that they preferred tools that allowed for a longer time to respond, such as texting, email, wikis, or shared databases for the transfer of information. Entire teams decided to use tools such as GroupMe (a group texting service that allows multiple participants to view and respond to text messages) as their tool of choice for day-to-day communications. These types of tools allowed students to receive a message, think about the implications of that message, and then respond appropriately when most convenient.

Recommended tools for middle stages In summary, for the middle stages of a virtual team similar to AerosPACE, we recommend giving extra consideration to the following communication tools, based on our experience and the literature reviewed:

- Web Conferencing (for periodic team meetings)
- Shared Database tools (such as MS Sharepoint or Google Drive)
- Email
- Text messaging, including group texting
- Shared virtual annotation and drawing tools

These tools help a team with mixed schedules collaborate effectively as the design evolves. The tools are also key in keeping record of critical design decisions, until the design is finalized and released for manufacturing.

Late Stages

The late stages of product design for projects such as AerosPACE include Early Full Prototyping, Testing, and Final Manufacturing. Although significant prototyping should have been performed prior to these stages, this portion of the project is characterized by an even more distinct shift from digital to physical work.

During these stages, small changes may be made to the design, depending on the need and time allotment, but for the most part, the team is now focused on manufacturing and full-scale testing. Physical parts are shipped to and from different team members' locations for assembly

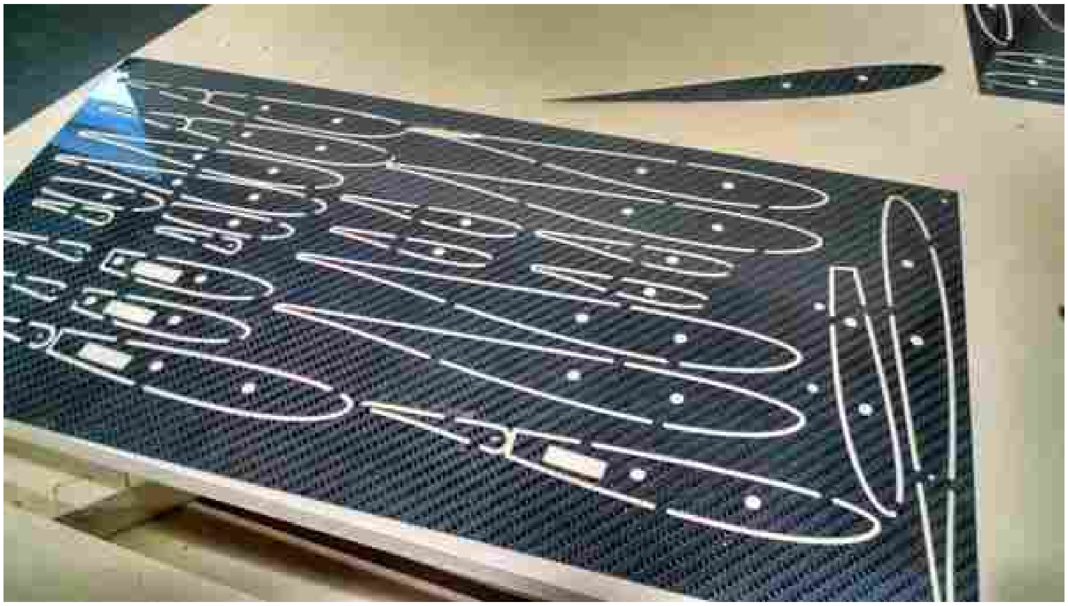


Figure 6.10: Photo of carbon fiber ribs sent by Team 4 over social media to show progress of manufacturing, during the AerosPACE 14-15 academic year.

and testing. Finally, the teams engage in a “Fly-off” in which they (attempt to) demonstrate their UAS in flight.

While computer-based design and analysis work is relatively easy to document and communicate to remotely located teammates, physical work is not. We observed some individuals on AerosPACE teams develop an interesting technique to overcome this challenge during the middle and late stages. The students we observed would use their phones to take quick photographs of themselves and/or their teammates performing work on physical items and would then post the photo to a team web-page, send it out in a group email or text, with a short caption, such as “Brand spankin’ new carbon fiber ribs!” (see Figure 6.10 below). These photos served multiple purposes. Perhaps most obviously, they allowed remote teammates to observe their work, identify potential errors, and offer suggestions. As well though, and no less important, they served to increase trust among geographically distributed teammates. The photos confirmed that teammates at distant locations were actively contributing to the work of the team, even if no digital progress was apparent.

Teams’ ability or inability to communicate effectively in the early and middle stages is often made clear in this stage when parts from various locations either assemble and function well as a whole, or do not. In our experience from AerosPACE, even the best teams will experience the need to re-work or adjust some portion of their design during the late stages, if not from prior miscommunication, then from a crash landing or accident that breaks some component.

For those reasons, teams must continue to communicate effectively and understand which collaboration tools best fit their needs at this point. In the late stages of the product development process, the team should focus on how the task is to be accomplished [80] and try to limit the amount of emotion that may be conveyed in the communication [139]. Hinds and Bailey's suggestion is based on their proposition that high levels of emotion in communication on distributed teams contributes to increased levels of conflict and reduced performance. Maruping and Agarwal hypothesize that virtual teams during the later stages of development should use communication mediums that are low in time to response and symbol variety, and high in parallelism, and durability [80].

In our experience in AerosPACE, student team members in the late stages of the project need tools that provide medium or high permanence, allowing them to recall exact values and specifications. Along with this, and similar to the middle stages, the socially acceptable time to response for the communication method selected should be longer to allow communicators to determine correct responses, which often involves looking up a value or identifying a specific part or process. For most teams we have observed, these requirements translate into use of tools such as group or individual texting and use of shared data sources. These findings generally agree with the findings of other researchers, such as Maruping and Agarwal [80].

High parallelism and high accessibility are necessary to coordinate the efforts among multiple manufacturing groups in a timely manner. Easily accessed communication allows double-checking of numbers and dimensions before the final manufacturing or assembly process takes place. High symbol variety becomes unnecessary as the teams are simply coordinating efforts of the manufacturing and shipment of parts, rather than making design decisions or resolving conflicts [140]. Moderate durability is helpful for when the team makes changes to the overall design and needs to accurately record the change made. When designing for manufacturing, it's critical to thoughtfully consider all the necessary steps for production of any product [141].

In the beginning stages of manufacturing, we found that email and data sheets will still be highly used. Team members reference the data sheets often as they configure manufacturing plans

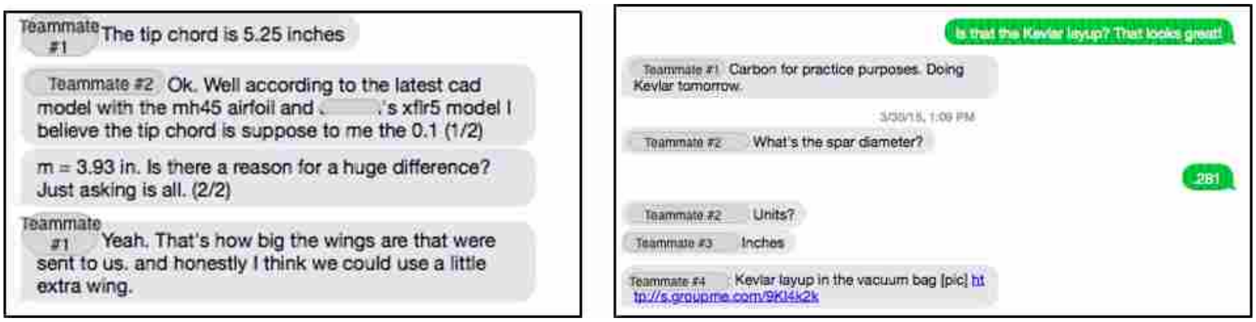


Figure 6.11: Examples of group text messages among teammates from Team 4 during the late stages of the product development process during the AerosPACE 14-15 academic year.

and email back and forth for clarification or to notify of changes. Once testing has been done on the full-model prototypes, a data sheet should be employed to show the results of the test followed by an email with suggestions for further action. The durability of these two methods makes it the best when creating a manufacturing plan across different locations.

While it may not be widely recognized as a proper form of communication in professional settings, texting is often a useful tool within engineering design courses. The accessibility of texting is high, the socially acceptable time to respond is long enough to enable a user to formulate a proper response, and the ability to easily look back at messages sent and their order demonstrates its high permanency. Furthermore, the high parallelism of texting allows for coordination efforts among multiple IPTs to occur at the same time with little effort. Figure 6.11 shows two examples of messages exchanged by Team 4 during the 2014-2015 AerosPACE program during the late stages of the product development process. The conversation on the left shows two teammates quickly verifying a design decision. The conversation on the right shows how texting allows one teammate to easily commend the efforts of another, and then later help verify a critical dimension. Both are good examples of how texting allows for more efficient coordination due to the high accessibility, low time to response, and high permanency.

Finally, our experience has shown that in the final stages of a project like AerosPACE, it is highly effective to allow at least some teammates from different locations to work on-site with their other teammates. This idea is supported by research by researchers such as Hinds and Bailey, who also cite Grinter et al. [139, 142].

An example from the 2014-2015 academic year of the AerosPACE program helps to illustrate this point. Team Bear had already completed and successfully flown a prototype of their UAS, but decided to make some last minute upgrades and tweaks. Only a week before the final fly-off, they rebuilt and rewired their UAS. Due to a faulty electronic speed controller, their otherwise improved UAS was unsuccessful and crashed spectacularly. While most of the team was disheartened, later than night, a few began texting the group in GroupMe asking if anyone wanted to try to fix the airplane. The team members all quickly responded that they would help and with their combined effort were able to completely repair the damaged plane. The next morning, they successfully flew their UAS and demonstrated its full capabilities. This feat was accomplished (at least in part) due to the text messaging and physical presence of the team members (in town for the fly-off).

Recommended tools for late stages In summary, for the late stages of a virtual team similar to AerosPACE, we recommend that extra consideration be giving to using the following communication tools, based on our experience and the literature reviewed:

- Shared Data Editing
- Email
- Text Messaging (including using phone cameras)
- Forums or discussion threads
- Face to Face Meetings

These communication tools are essential for allowing a team to quickly access and verify design parameters during manufacturing. They also allow for smoother integration of completed parts in the final product.

6.4 Trunking

One trend we observed during the Taxonomy experiments (explained in chapter 4) was the types of strategies teams employed to try to deal with "trunks." Following the idea that a part's dependency branching is similar to the structure of a tree, the first element of the tree structure, as we imagined it (see Figures 4.2, 4.3, and 4.4 for example) was a single feature created by one user which gives the rest of the MU team the context it needs to model other features. While in theory, many different features of a part could be chosen as the trunk, the classification process identified features which seemed to be the most likely chosen as the trunk. We assumed that most teams, for the sake of avoiding confusion about how the part was oriented, would choose to follow a "single trunk" strategy. The obvious drawback to this strategy is that the rest of the team must wait while one person creates the trunk.

Test volunteers were not informed or instructed how to organize their modeling efforts, and we observed that most teams did follow a single-trunk strategy. However, we also observed several enterprising teams attempt to improve on the single-trunk method for MUCAD modeling. Some teams would attempt to "shrink" the trunk of a part (during whose development all but one teammate must wait) by having one user complete a very simple version of a sketch of the trunk feature. The user who sketched this initial feature would then quickly exit the sketch to allow the other team members to view it. In many cases, the sketch was not completely constrained or even dimensioned correctly, but sufficiently communicated the general size, shape, and orientation of the feature well enough for the other members of the team to begin to create their features. Often, the initial user who modeled the trunk would return to refine it later on.

One example of this strategy can be seen in Figure 6.12, where, after discussing their strategy, one user created a very rough, incomplete sketch. He then exited the sketch so it would be committed to the server and his teammate could see it. Then, he reentered the sketch to refine it while his teammate began working on other portions of the model.

Other teams attempted to "multi-trunk" their parts. After attempting to explain the general orientation of the part's features to each other, two or more team members would simultaneously sketch and create their features. The risk taken by teams that attempted to multi-trunk, of course, was that once completed, their features would sometimes not properly relate to each other. Sometimes this took little effort to correct, while other times it meant completely redoing features and increased confusion among teammates. In most cases, multi-trunking required much more effective coordination before initiating modeling activities. Future research should investigate this tactic, its potential, and implications.

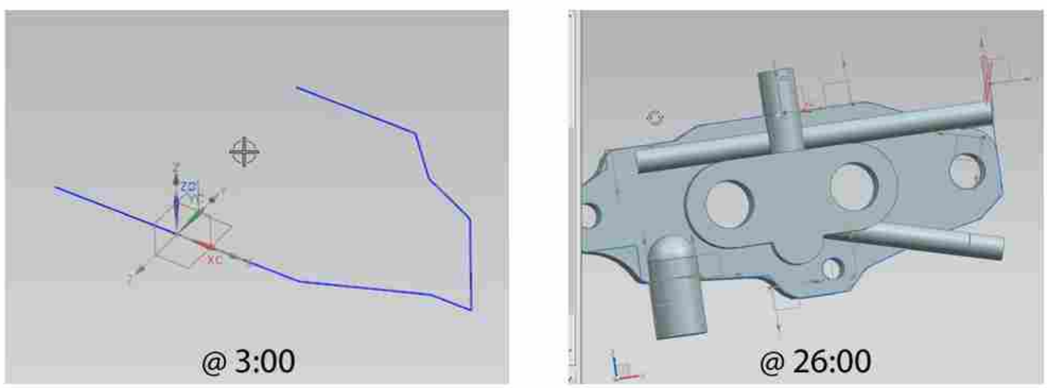


Figure 6.12: Example of a rough-trunked initial sketch (left), and the more fully developed model (right).

CHAPTER 7. MINIMIZING PROCESS LOSSES BY IMPLEMENTING NOVEL NEW MULTI-USER TOOLS

7.1 Introduction

As mentioned in the background chapter and mentioned briefly in the "Minimizing Process Losses by Implementing Effective Multi-User Strategies" chapter, the literature and experience with the AerosPACE program point to a need for a MU virtual annotation and drawing tool to help reduce $Losses_{pcs}$. This chapter provides an in-depth investigation into the inspiration for and an experiments testing the usefulness of such a tool.

7.1.1 Introducing Telestrator

To aid in the early concept stages, when many researchers agree that sketching is a common ideation practice [88, 95], we developed a basic collaborative sketching application (CSA) prototype casually called "Telestrator" which we believe possesses the requirements listed in the background chapter. Built on a client-server architecture, the Telestrator provides a simple interface where users can collaboratively sketch their ideas simultaneously on a shared canvas. Built-in audio allows users to communicate as if they were all standing around a whiteboard together.

One user starts and names a session. Others can then select and join the session from the file-menu. Names of the users active in the session are displayed in the ribbon bar at the top of the window along with a color that corresponds to each user's cursor as shown on the sketch canvas. Basic drawing and annotation tools, similar to those found in MS Paint, including basic shapes, free-form and straight lines, double and single-headed arrows, and opacity controls, are accessed in the ribbon area, as can be seen in Figure 7.1. The user who starts the session can choose to begin with either a blank canvas or load a saved image or take a screenshot for the background of the canvas. During the session, any user can use the Add Image button to load a saved .jpg image to the canvas, where it can be resized and positioned.

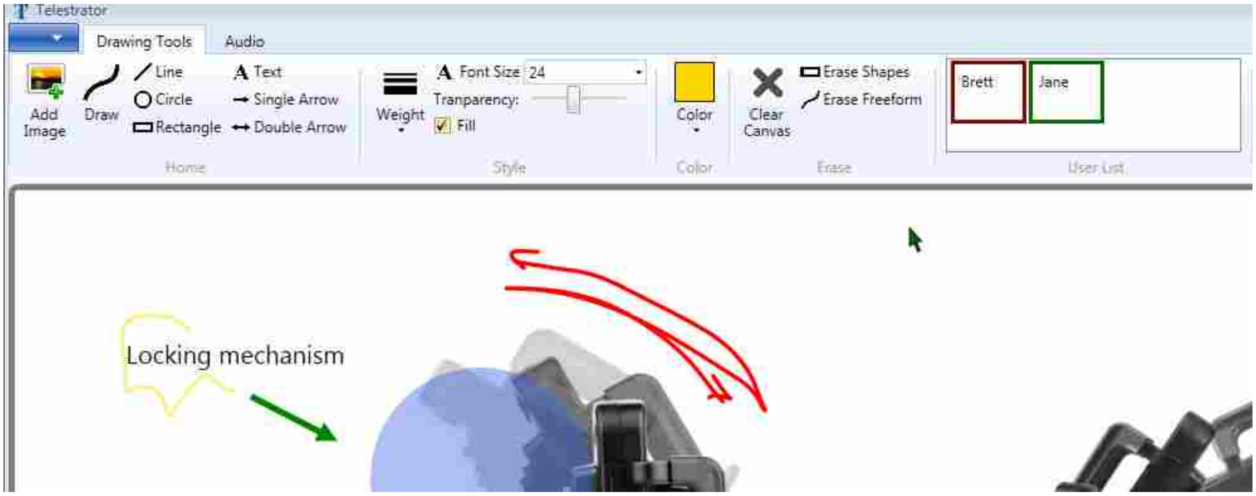


Figure 7.1: Drawing, annotation, and other tools are accessible via the ribbon-style menu at the top of the window. Effort was made to select only features that are very simple and easy to learn how to use. Current session users can be seen along with the color of their cursor.

To enable users to emulate the gesturing and hand-motions that are common during in-person design sessions, Telestrator users can see all users' cursor movements in real-time, as well as lines or other objects as they are being drawn. Telestrator also includes a Temporary Draw feature that allows users, while holding the control button, to draw a line or shape. Once the control button is released, the drawn shapes disappear, enabling a user to temporarily highlight a specific region or indicate motion while conversing with other users via the built-in audio communication tool (or other tools like Skype or a telephone call). Since it was built using Windows Forms, the program can be run on both desktop and Surface tablet PCs using either mouse, touch, or stylus inputs. Sessions can be saved and re-opened and the canvas can be saved as an image. The contributions of specific users in a session can be viewed by selecting the user's name in the user list. That user's contributions are then highlighted in a specific color.

An example of how the tool functions similar to a virtual whiteboard can be seen in Figure 7.2. These periodic screenshots show the sketches of two users (one in Utah, the other in Washington state) discussing attachment mechanisms for a portion of a UAV in the early stages of design. They start by sketching ideas, then add different perspectives, erase some items, then add others.

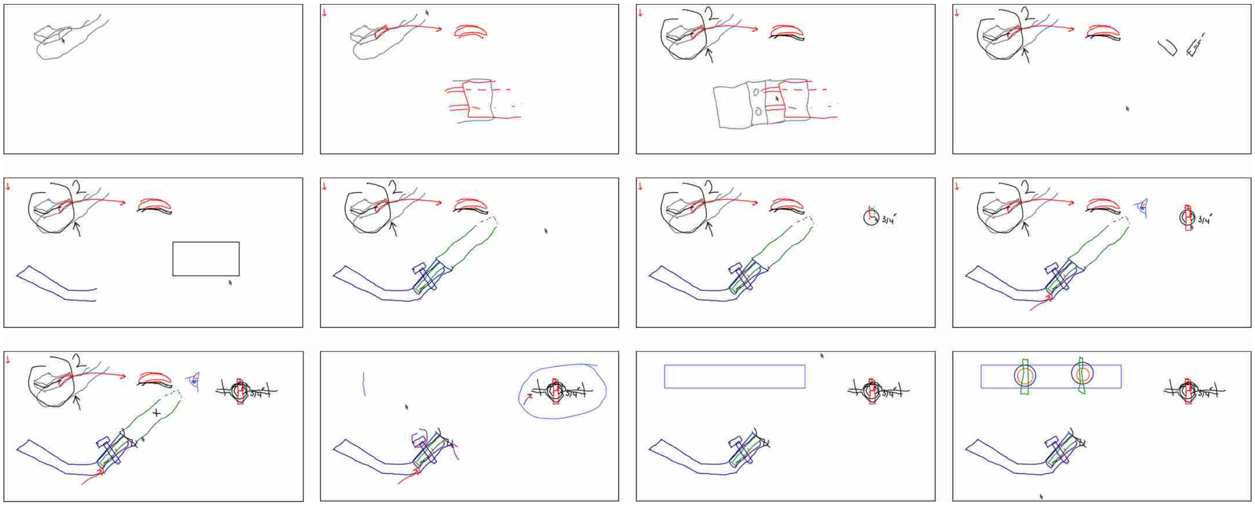


Figure 7.2: Progression of a Telestrator session (left to right and top to bottom) showing how multiple users treat the tool like a whiteboard simultaneously adding and later deleting quickly sketched ideas regarding the design of a removable wing attachment for a UAV.

7.1.2 Theory

To explore how a virtually shared sketching tool can enhance virtual engineering design team performance in the early stages of the design process, we developed a set of exploratory questions:

- How well do members of a virtual team using the tool feel they understand each other's ideas compared to members of a collocated team using a traditional whiteboard? Compared to a virtual team with just an audio connection?
- How does having the tool affect the level of frustration/pleasure a team member experiences during the early phases of the design process compared to a collocated team using a whiteboard, or a virtual team with only an audio connection?
- Will members of a virtual team using the tool feel they are able to contribute more equally to the design process than when they are working as a collocated team at a whiteboard or as a virtual team with just an audio connection?
- Considering different situation/tool combinations, in what order will team members prefer to work?

Table 7.1: The order in which teams were introduced to different situations and design challenges was varied to enable more objective comparison of user experiences.

	Design Challenge			
	Can Crusher	Corn Processor	Wave/Tidal Energy	Coin Sorter
Conference Room Whiteboard	Teams 1 & 5	Teams 2 & 6	Teams 3 & 7	Teams 4 & 8
Telestrator on PC	Teams 4 & 8	Teams 1 & 5	Teams 2 & 6	Teams 3 & 7
Telestrator on Tablet	Teams 3 & 7	Teams 4 & 8	Teams 1 & 5	Teams 2 & 6
Virtual without Telestrator	Teams 2 & 6	Teams 3 & 7	Teams 4 & 8	Teams 1 & 5

7.2 Lab Experiment

To investigate the questions presented above, an experiment was designed. Teams of three students were given four design challenges (10 minutes each) to complete using different tools in different situations: together in a conference room using a whiteboard, virtually with the Telestrator and audio communication, and finally, virtually with only audio communication (Skype group audio). Subjects completed a survey with questions related to each hypothesis after completing the design challenges. Screenshot examples from each of these activities can be seen in Figure 7.3.

The order in which each team experienced each tool/situation combination (seen in Table 7.1) was varied to attempt to mitigate potentially confounding factors such as memory bias, learning, or improving team performance. Worinkeng et al. found that after warming-up with a pre-sketching activity, individuals tend to produce more novel solutions to design problems [143]. We were concerned that teams might improve their ability to generate ideas after their first design challenge, thus biasing their impression of the effectiveness of a given tool. Although varying the order in which teams were presented with each scenario should reduce the effects of this possibility, we attempted to further mitigate the risk by implementing a 10 minute pre-sketching activity similar to the one described by Worinkeng et al. Finally, each experiment was completed by two teams as an attempt to provide a more significant number of data points.

Undergraduate student volunteers who completed the experiment included students from a variety of majors. The majority (58 percent) were studying mechanical engineering. Other majors represented included: industrial design, computer engineering, manufacturing engineering, applied physics, chemical engineering, and history. Teams were formed based on volunteer availability. Each design challenge was meant to simulate the kind of situation an engineering design team

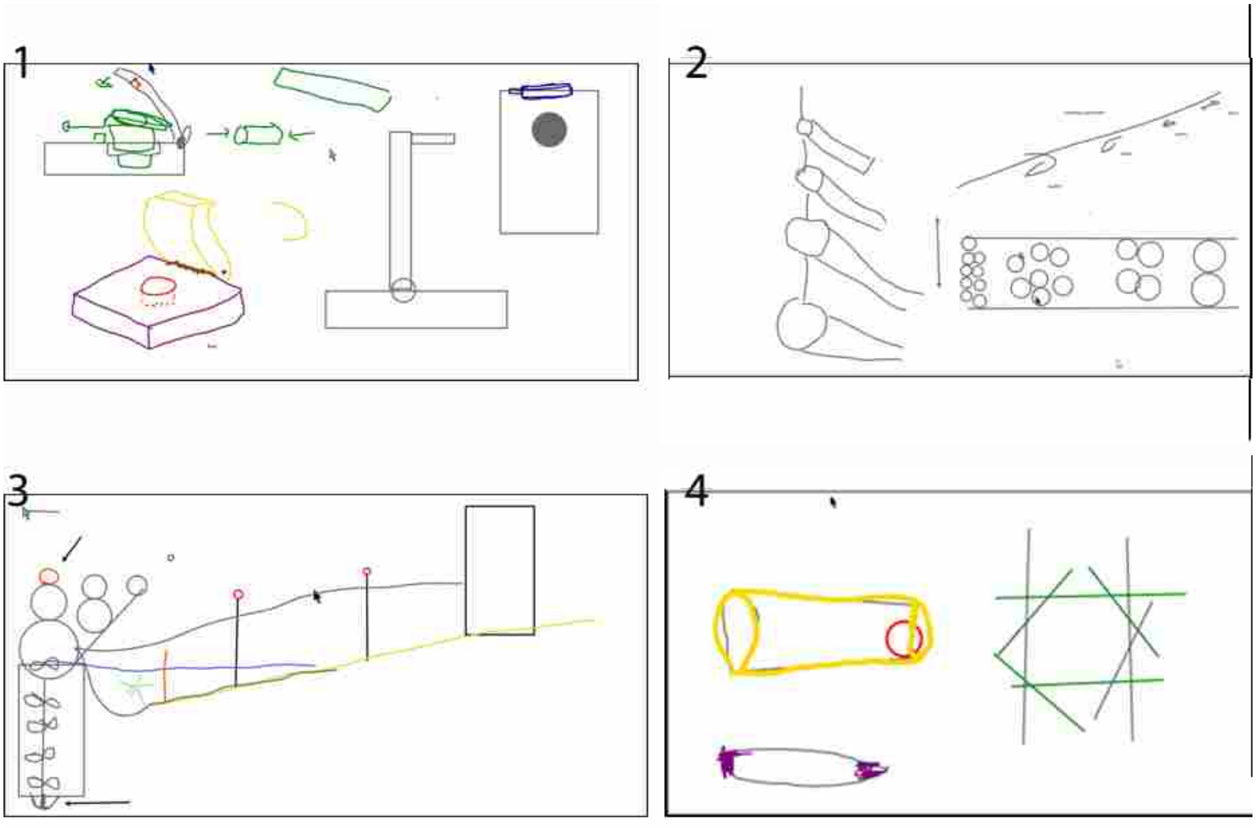


Figure 7.3: Example from different teams' sessions where they generated ideas for (top left to bottom right): 1) A human-powered aluminum can crusher, 2) An automatic coin sorter, 3) A combined wave/tide electricity generator, 4) A method for removing kernels from cobs of harvested corn.

might face in the early stages of conceptual design and that could be completed in the time allotted. Similar to Worinkeng et al., we chose design challenges that we felt all students would be able to easily relate to without any specialized knowledge [143]. Each challenge was read to the students:

1. Can Crusher: As a team, you have been commissioned by the university recycling center to design a new, human operated soda can crusher. It must be easy and safe to operate.

2. Corn Processor: You work at the food processing company Allcorn. As a team, you have been given the assignment to develop a new, automated process for removing kernels of corn from the cobs (the cobs have already been shucked). Brainstorm new ways to remove the kernels.

3. Wave/Tidal Energy: In post-apocalyptic San Francisco, electricity is scarce. But, you and your friends have an enterprising idea to harvest energy from the tides and waves in the bay. Brainstorm how to build your combined wave / tide electricity generator.

4. Coin Sorter: As a new hire at the startup bank Spendthrift USA, you have noticed that a lot of poor college students bring in jars of coins that the clerks have to sort by hand. Design an inexpensive solution that automatically sorts (American) coins and counts them.

Immediately before teams used the Telestrator for the first time, they watched a training video and were given the opportunity to ask questions. The training video explained how to start and join a Telestrator session, and how to use the different features and tools in the program. Subjects were also given the chance to ask questions, and proctors were available during the tests to assist if subjects had questions.

7.2.1 Results & Discussion

Due to a software bug that occurred with the tablet version of the Telestrator, the software for the tablet version had to be updated partway through the experiment. Thus, we will not integrate the results from the tablet based experiments into our conclusions.

The post-experiment surveys were designed to investigate the research questions posed in the section Theory.

QUESTION 1: The first question asked if virtual teams using the Telestrator would understand each other's ideas better than virtual teams without the Telestrator and about as well as collocated teams using a whiteboard.

Results from the post-experiment survey tabulated in Table 7.2 show that respondents felt that the Telestrator made understanding teammate ideas much easier than when working remotely with only an audio connection, though it was still not as easy as being together in the same room. When asked to rank-order the tools they used in the experiment according to how easy the scenario (tool and situation) made it understand teammate ideas, nearly all respondents agreed that using the Telestrator made it easier to understand each other's ideas than working with only an audio connection. Working remotely with the Telestrator was ranked second compared to working in the same room with a whiteboard. The full distribution of votes can be seen in Table 7.2. Scores were

Table 7.2: Distribution of votes regarding ease of understanding teammate ideas given different situation/tool settings.

	Scenario		
	In-Person With Whiteboard	Separated on Desktop With Telestrator	Separated With Audio Only
1st Place Votes	21	1	0
2nd Place Votes	1	14	1
3rd Place Votes	0	7	1
4th Place Votes	0	0	20

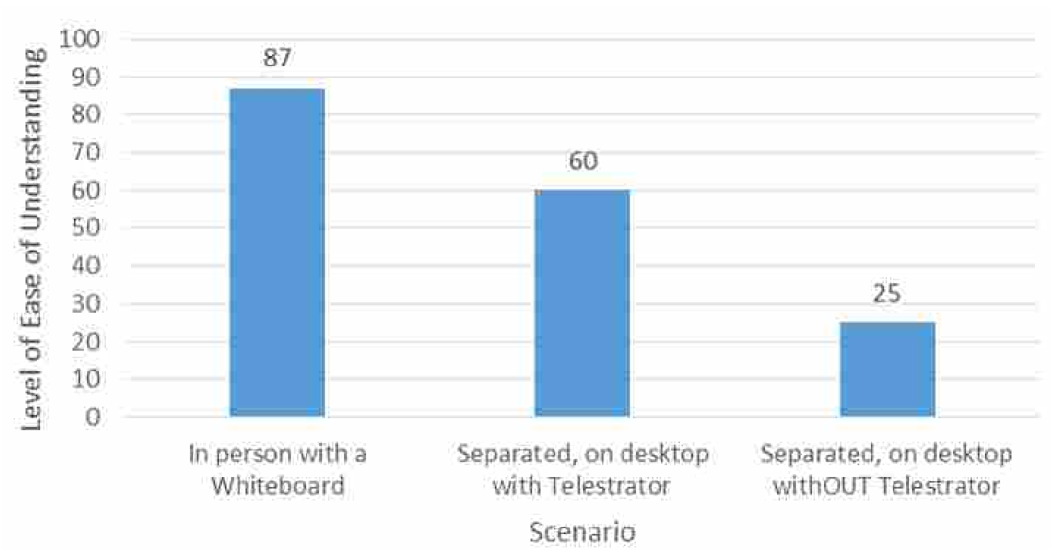


Figure 7.4: Weighted and summed votes illustrate the difference respondents found in how easy it was to understand teammate ideas in different settings.

assigned to each ranking respondents gave and were then summed as shown in Figure 7.4 to give each tool an overall score related to how easy respondents felt the scenario made it to understand each other's ideas. A first place ranking was worth 4 points, second place was worth 3 points, third place 2 points, and fourth place 1 point (working remotely with the Telestrator on tablet was originally an option, as explained above).

The fact that respondents nearly all found the Telestrator to make such a difference in how well they understood each other's ideas when working remotely is encouraging. In the survey, one respondent said that the Telestrator, "appeared to be an effective way to communicate ideas over a distance and simulate the experience of being in the same room."

QUESTION 2: The second research question asked if members of virtual teams using the Telestrator would experience lower levels of frustration/higher levels of pleasure than members of virtual teams without the Telestrator and even than members of collocated teams using a whiteboard. Subjects were told to “indicate your level of frustration or pleasure with each situation/tool,” and responded using a Likert scale graphic slider gauge, indicating their level of frustration/pleasure with each tool by changing the expression on a “smiley face” icon.

The respondents indicated that using the Telestrator was less frustrating/more pleasurable than working virtually with only an audio connection. The average frustration/pleasure score (0 to 5, with 5 being completely happy with the experience) for virtual collaboration without the Telestrator was only 2.04 out of 5.00, while the average score for virtual collaboration with the Telestrator was 4.17 out of 5.00. Levels of pleasure were rated more highly when working in the same room compared to working virtually with Telestrator. However, the difference between the two is much smaller than the previous comparison, with the average rating for collocated work being 4.92 out of 5.00. Figure 7.2.1 shows the frequency of different ratings for each.

This finding, that working with a tool like the Telestrator significantly decreases one’s frustration with working in a virtual environment, even to a level that may be comparable with working in the same room on a whiteboard, is significant. Hinton found that when attempting to perform creative problem-solving tasks, environmental frustration significantly reduces performance [144]

QUESTION 3: Question three asked how equally test subjects would feel that each team member had contributed to the design in each setting. Results from the survey indicate that feelings regarding the equality of individual teammate contribution was nearly indistinguishable between in-person teamwork and working in separate locations with the Telestrator. On a scale of one to three, with three being completely equal, students gave the collocated setting a 2.66 average rating, and working separately on the Telestrator a 2.64 average rating.

Figure 7.6 shows, however, a larger difference between respondents’ feelings regarding equality of contribution for working remotely with the Telestrator and working remotely with just an audio connection. The average equality rating for working remotely with just an audio connection was 2.34.

To compare these means and determine their statistical significance, we first performed an ANOVA, followed by a Tukey-Kramer Honestly Significant Difference (HSD) test [145]. An

Frustration / Pleasure Level	Scenario: In Person with Whiteboard	Scenario: Separated on Desktop With Telestrator	Scenario: Separated With Audio Only
1	0	0	10
2	0	0	5
3	0	3	7
4	2	14	2
5	22	7	0

Figure 7.5: Indications of frustration/pleasure with each scenario.

ANOVA showed that at least one of the means is significantly different than the others (p = 0.013). Next, the Tukey-Kramer HSD showed that at a 95 percent confidence level, the difference between the Separated with Telestrator and Separated with Audio Only means is statistically significant (p = 0.040). As well, the difference between the In-Person with Whiteboard and Separated with Audio Only means is statistically significant (p = 0.015).

These findings indicate that a difference in perceived equality of teammate contribution is significant between working in a distributed environment with only audio communication and working in the same room with a whiteboard. It also shows that by using a virtual tool such as the Telestrator that this difference can be effectively eliminated.

QUESTION 4: The fourth and final question asked in what order test subjects would prefer the different scenario options. More respondents gave their highest preference to working in a co-located space than any other option (see Table 7.3). The second highest number of first preferences and highest number of second preferences went to working on a virtual team using the Telestra-

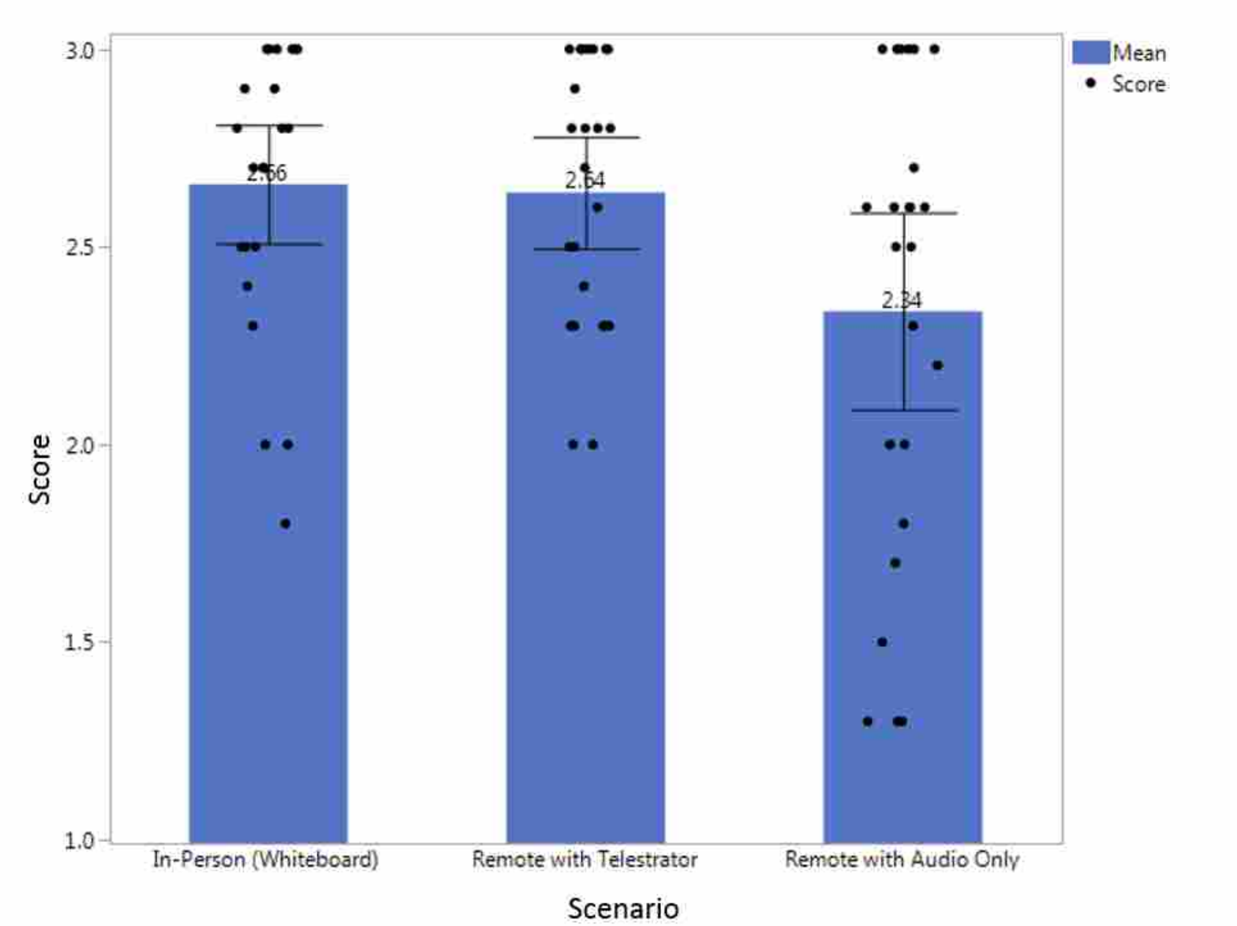


Figure 7.6: Test subject ratings regarding equality of teammate contribution in each scenario. Individual data points and 95 percent confidence intervals are also shown for each.

tor. No respondents indicated they would give highest preference to working virtually without the Telestrator, even when given the chance to describe some "other" type of tool.

The fact that some respondents actually preferred using the Telestrator to work virtually compared to working in the same room as their teammates is similar to what French et al. found in their research on teams of serious Minecraft players who designed and constructed large, complex structures [42]. One respondent explained his reason for preferring using the Telestrator to collaborate virtually over same-room collaboration by pointing out that

> "The white board is easiest to control, but Telestrator allows one to reuse older images and designs created."

This sentiment echoes points made by Chandrasegaran et al. [95].

Table 7.3: Preference order of survey respondents (1 = first choice). While most preferred to work in-person with a whiteboard, some stated their first choice would be to work virtually using the Telestrator. None chose working remotely without Telestrator as their first or second choice.

	In-Person with a Whiteboard	Remotely Located with Telestrator	Remotely Located withOUT Telestrator	Other
	1	2	4	5
	1	3	5	2
	1	4	5	3
	1	2	4	5
	2	1	4	3
	1	2	4	5
	1	3	4	5
	1	3	5	2
	1	3	5	2
	1	2	3	5
	1	3	4	5
	1	2	5	4
	1	2	4	5
	1	3	5	2
	1	2	4	5
	1	4	5	2
	1	2	4	5
	1	2	5	4
	1	2	4	5
	1	2	4	5
	2	1	3	5
	1	4	5	3
	1	3	5	2
	1	3	5	4
Average	1.08	2.5	2.62	3.69
Percentage of First Choice for Remote Collaboration Tool	-	45.8%	0.0%	25.0%

The high number of “other” mentions in the second choice position merits closer examination. Five respondents indicated “other” for their situation/tool of second choice. Three of those who chose this option explained they wanted to use paper and pencil together in person. One explained wanting to use the Telestrator remotely but with text-chat capability, and one wanted video-conferencing. Note that the percentages on the bottom row of Table 7.3 do not add to 100 percent for remote collaboration because of a) exclusion of Telestrator on Tablet data; b) the fact that some respondents preferred remote work with Telestrator over in-person work.

7.3 AerosPACE Case Study

In addition to a laboratory based study, we examined the use of the Telestrator in a more real-world, virtual engineering design team situation. Aerospace Partners for the Advancement of Collaborative Engineering, or AerosPACE, is a multi-university, multi-disciplinary capstone program sponsored by the Boeing Company. Teams composed of about a dozen students from multiple universities from across the United States of America work together for two semesters to design, build, and fly an UAV [146–148]. Students traditionally use tools such as text messaging, phone calls, teleconferencing, web-conferencing, and email to collaborate between their different geographic locations.

Near the beginning of the 2015-2016 program year, students involved in the AerosPACE program (n=72) received copies of the Telestrator tool as well as training during scheduled lecture time on how to install and use the tool. Training videos and other material were also posted on the program’s MS SharePoint site where all students could access them. At the end of the first semester students completed a survey which included questions regarding their use of the Telestrator tool related to the hypotheses of this study. Approximately 93 percent of students responded to the survey.

Examples of how the Telestrator was used by AerosPACE students include the images shown in Figure 7.7. Here, two students, one at Brigham Young University in Utah, and one at Washington State University were working together during two different Telestrator sessions to develop ideas for the structural portion of their team’s UAV. For the background in one session they used a blank canvas and in another, they took a screen-shot of a slide from a presentation made by a team in a previous year. Speaking of the session in which they used a screenshot of the previous team's presentation, one of the students said,

> "It was really helpful to be able to have a picture there and then being able to draw over the top of it and say, 'along this specific axis, this is what I was thinking of where the force would be applied'"

This same student explained how they chose to use the Telestrator to collaborate over distance. They had been talking using a video-conferencing application, trying to explain their ideas verbally and with hand motions. "I can use as many hand motions as I want to, but if he's not able to visually see my five different hand motions coming together, it's not going to work." He went on to say that with Telestrator, he could create drawings that enabled him to tell his collaborator that when he circles something, this is what he's referring to, making it much easier to explain what he's thinking when he says the bolt should go through a certain shaft, or that two connections should occur in a certain location, etc.

In general, the reaction of students in the AerosPACE program who had chosen to use the Telestrator significantly was very positive. Since some students were not able to use the tool due to software installation restrictions having to do with rented laptops and campus computer labs and some students simply did not use the tool, we consider the responses of two different sub-groups from the AerosPACE program that did have significant experience with the tool. First, the members of team five, consisting of ten mechanical and aeronautical engineering students from Clemson University, Tuskegee University, and the Georgia Institute of Technology. The second group consists of all other students who reported using the Telestrator two or more times. Together, these two sub-groups include 14 students representing four different teams and six universities.

Those who used the tool appear to have had significant success doing so. Examples of images from their sessions can be seen in Figure 7.2 and Figure 7.7. These images confirm what a student team leader from Clemson University on team five stated in an interview, that one of the most common uses of the tool was to help explain ideas related to the structure of the UAV, determining collaboratively how to connect wings, frames, and other elements. In Figure 7.2 ideas from two different students regarding how to best connect a wing to the fuselage are sketched out. Figure 7.7 shows two different images. The top image shows both a side view (top left) of an

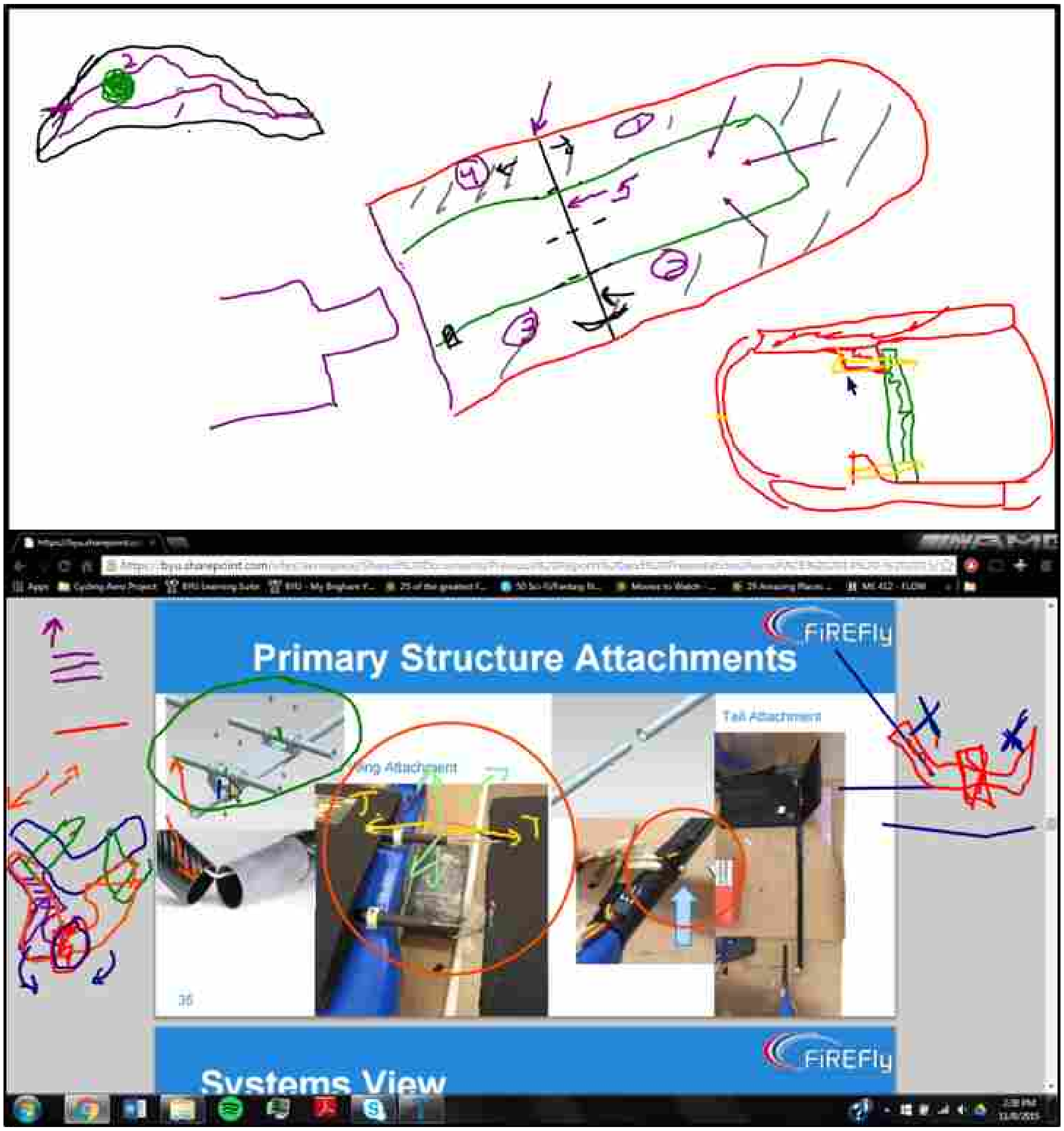


Figure 7.7: Screenshots from part-way through two different Telestrator sessions, each involving two teammates at different locations, one at Brigham Young University (Utah), the other at Washington State University. The session on top shows a blank canvas used as the background; the one on the bottom demonstrates using an image (a screenshot) as a background. The image is from a presentation by a team from a previous program year.

airfoil, as well as a cutaway view (center) of a part of a wing attachment. In the bottom image, the students used the Telestrator to take a screenshot of a slide from a project from a previous year of AerosPACE and ”piggyback” off of the previous team’s ideas regarding attachment strategies.

Examining these 14 students’ use of the tool and their responses to a survey generally confirms the results of the laboratory experiment. When asked in the survey to rate their agreement with the statement, “Compared to working over the phone, with Skype audio, or similar, I feel like using the Telestrator has helped me and my teammates understand each other’s design ideas better,” no respondent disagreed, and over 70 percent agreed or strongly agreed. What may be more interesting are the responses when asked to rate their agreement with the statement, “Compared to working in the same room, I feel like using the Telestrator has helped me and my teammates understand each other’s design ideas better.”

More than one third of respondents agreed with this statement, while only 21 percent disagreed or strongly disagreed. See Figures 7.8 and 7.9 .

These results suggest that having the right tool to work with, in this case a MU collaborative sketching application (CSA), makes virtual work much more appealing, especially when compared to working virtually without it. As well, it seems to again corroborate the findings of French et al., that some prefer to work with a team in a virtual setting, even over working in the same room together [42].

AerosPACE students were also asked to rate their agreement with the statement, “I feel like using the Telestrator helped me and my teammates to contribute more equally to our design activities” compared to working in the same room, and compared to working over the phone, with Skype audio, or similar conference call service. As seen in Figures 7.8 and 7.9, respondents were mostly ambivalent when comparing audio-only and the Telestrator in this respect. However, more than twice as many respondents agreed compared to the number who disagreed or strongly disagreed.

These results seem to offer weaker support for the idea that a CSA such as Telestrator can improve equality of teammate contribution compared to the results of the laboratory experiment. The less structured manner in which AerosPACE students used the Telestrator may have contributed to this outcome. Still, some support for the idea that a CSA can improve the equality of contribution among design team members was found.

Finally, AerosPACE students were asked to order, according to their preference, collaboration situations and tools, from most preferred to least preferred. Table 7.4 shows respondent preferences, with 1’s representing a respondent’s first choice. Interestingly, in this area, the AerosPACE students differed markedly from the laboratory experiment students. These AerosPACE students

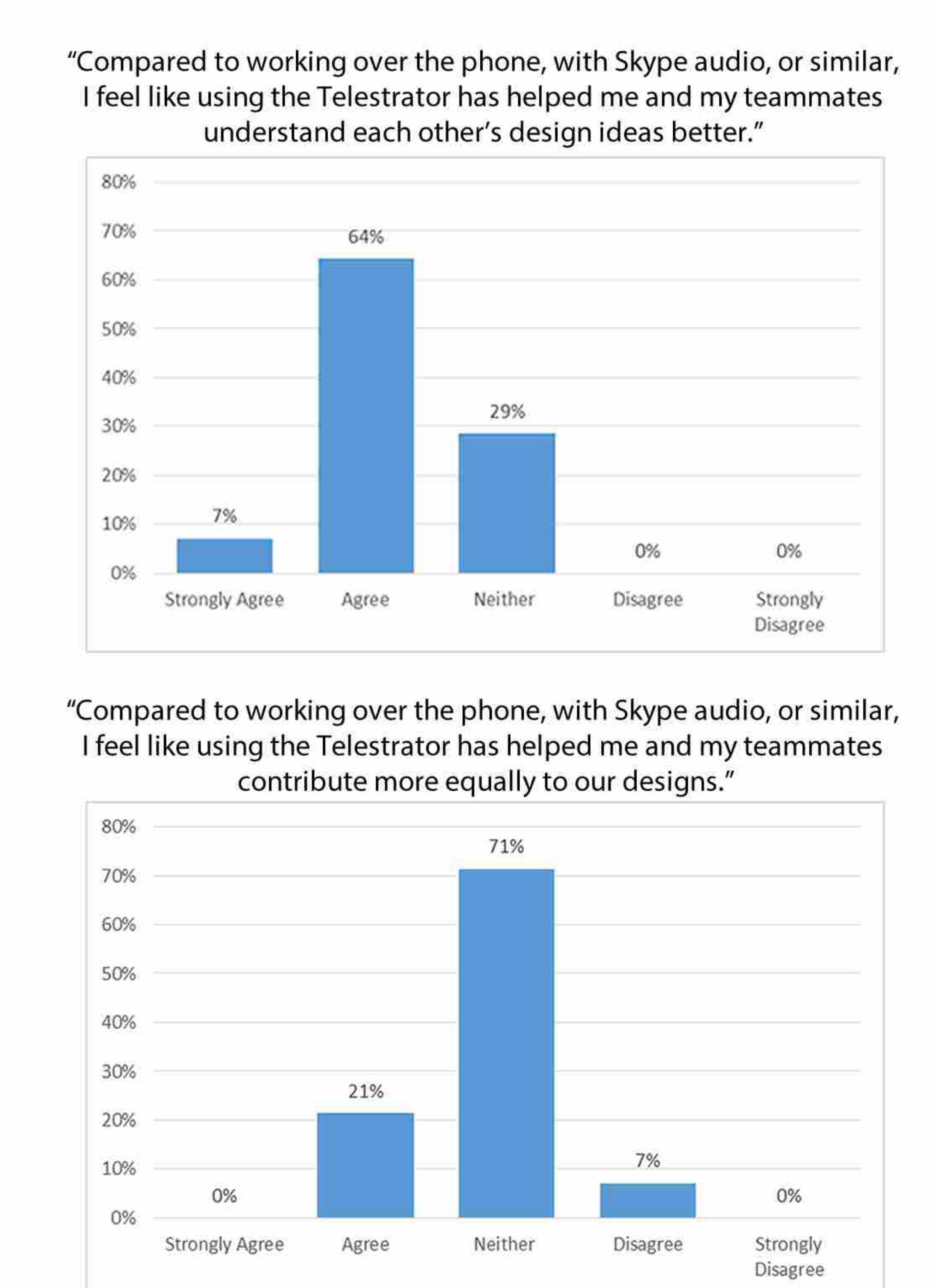


Figure 7.8: AerosPACE students' levels of agreement with statements regarding Telestrator's effect on their ability to understand and contribute to designs when working with their teammates using the Telestrator and when working virtually with only an audio connection.

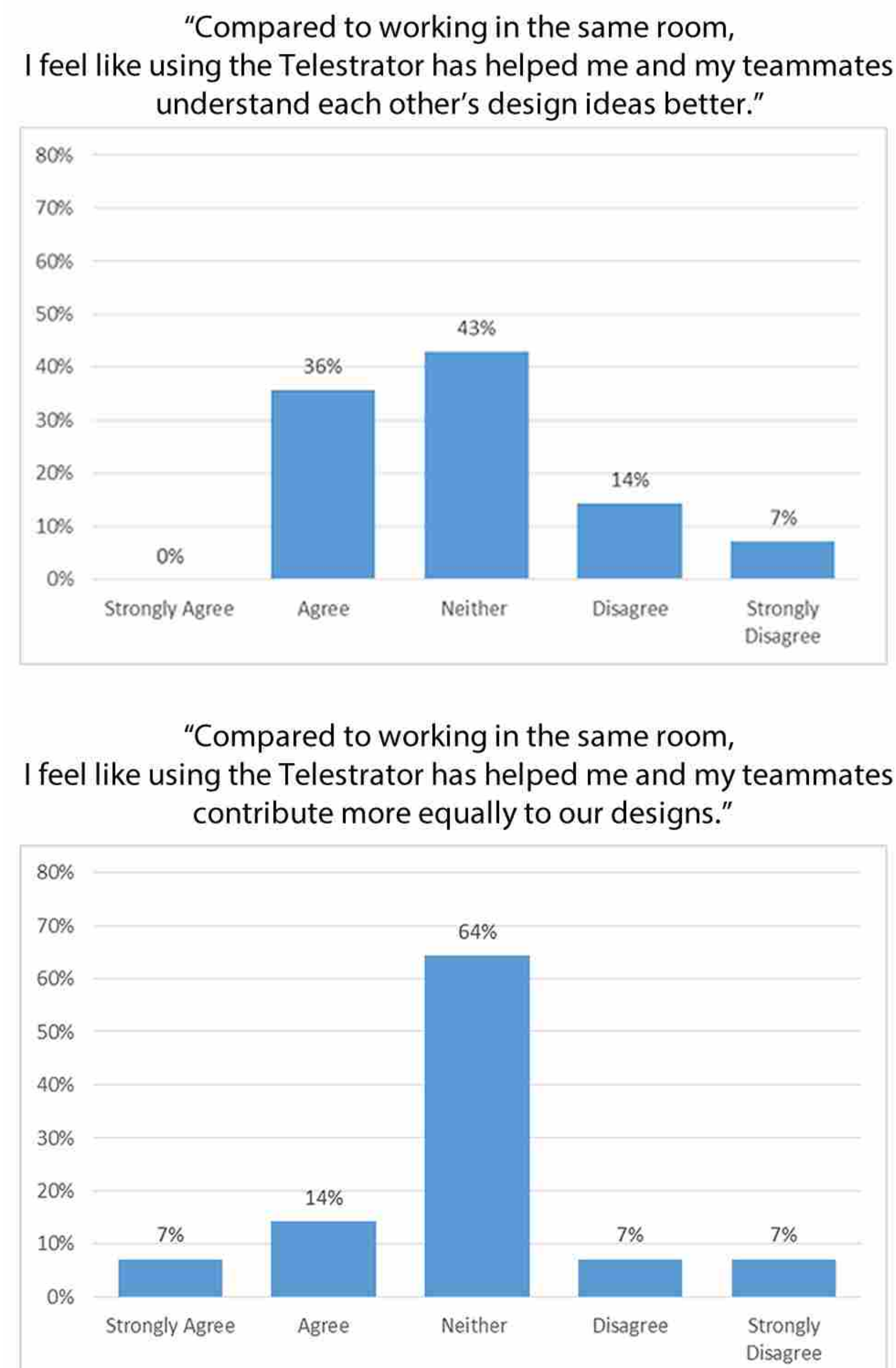


Figure 7.9: AerosPACE students' levels of agreement with statements regarding Telestrator's effect on their ability to understand and contribute to designs when working with their teammates using the Telestrator and when working together in the same room.

Table 7.4: Showing the collaboration tool preferences of AerosPACE students. All student most prefer in-person collaboration (1's). However, when considering only remote collaboration, AerosPACE students prefer to use the Telestrator a little over 30 percent of the time (2's).

	In-person (in same room)	Remotely located with Telestrator	Remotely located with audio (phone call, Skype Audio, etc.)	Remotely located with other tools	Other
	1	4	2	5	3
	1	4	2	5	3
	1	2	4	3	5
	1	3	2	4	5
	1	4	2	3	5
	1	2	4	3	5
	1	5	2	3	4
	1	2	3	4	5
	1	3	2	4	5
	1	3	2	4	5
	1	3	4	2	5
	1	2	3	4	5
	1	3	2	4	5
Average	1.00	3.08	2.62	3.69	4.62
Percentage of First Choice for Remote Collaboration Tool	-	30.8%	61.5%	7.7%	0.0%

indicated a higher preference on average for working remotely via audio only than working remotely through the Telestrator.

A variety of reasons for this difference are possible. Among the most likely is the fact that in the laboratory experiment, teams worked solely on tasks that, by design, incorporated a large amount of visual information. In the AerosPACE program, however the scope of work that must be accomplished by teammates collaborating from different location is much broader they must communicate and coordinate efforts on items as varied as who will present in the next design review to whether to use bolts or adhesive for a joint to how soon they need to order foam for the prototype wings. Clearly, the types of tasks they face include a much larger variety of tasks than the laboratory experiment, many of which are likely not good candidates for Telestrator collaboration. Analyzing the results from this perspective, the fact that Telestrator a tool none of them had used before was able to capture 30 percent of the respondents' first preference for remote collaboration is impressive.

One student from team five who ordered her tool preference as 1) In person, 2) remote via audio, and 3) Telestrator, explained,

> "Telestrator is good when sharing images, but unnecessary when sharing other things..."

Comments from other respondents with the same order of preference indicated that some students had not updated to use the most recent version of the tool, which may have also influenced their preference order.

CHAPTER 8. CONCLUSIONS

8.1 Introduction

In order to maximize the $Prod_a$ or actual productivity of virtual engineering design teams working with MU tools, I have addressed both maximizing $Prod_p$, or potential productivity and minimizing process losses: $Losses_{pcs}$. To do so, I have engaged in multiple experiments, case studies, and demonstrations. Figure 8.1 summarizes some of these outcomes. I conclude with the following thoughts on each factor:

8.2 Maximizing Potential Productivity

Maximizing potential productivity means that the organizer of the team must know a significant amount about both the work to be done and the people who are to do it. In a virtual team setting where teammates often have not met and cannot meet face-to-face on a regular basis, all while working with new, often unfamiliar MU tools, that becomes more difficult and important than ever. For that reason, I investigated methods for determining the optimal number of teammates when working in a MUCAD environment and principles and methods for developing a system to profile individuals who are candidates for virtual engineering design teams.

8.2.1 Identifying the Optimal Number of Teammates

By classifying a sample of parts using a taxonomic scheme we developed, we were able to test two proposed models for predicting the optimal number of MU team members for modeling a given part. The empirical data gathered through testing strengthen the idea that an optimal number of members exists for MUCAD teams, and that the optimal number of users can be predicted, with varying accuracy, by different kinds of models. We also found strong evidence to support the theory that increasing the size of a team, from a single user to larger teams can increase accuracy

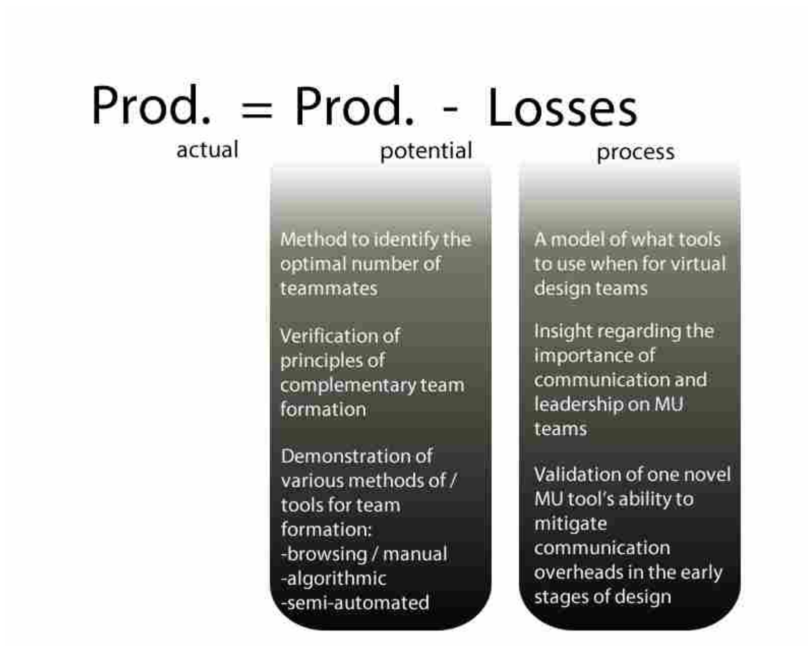


Figure 8.1: Steiner's equation with high-level conclusions regarding maximizing potential productivity and minimizing process losses.

when predicting the time for completion. This finding is significant for organizations that wish to improve their ability to estimate completion time for CAD models and thus improve their overall ability to estimate completion of a given project.

While the two linear models proposed did indicate a positive correlation between the optimal number of team members and the independent variable (number of features and average number of features per row of the feature dependency tree), the correlations were weak statistically. Logistic curve-fits were proposed which improved statistical significance and made more practical sense as well. More testing should strengthen these conclusions. We also found strong evidence to suggest further research in this area by fitting the time to completion versus the number of features by team size, which did reveal highly significant values.

Principles

Principles derived from this portion of the work include:

- By developing a taxonomy, we can better understand part designs in the context of MUCAD teams.

- Parts which display a linear feature dependency tree structure are not good fits for MUCAD teams regardless of the number of features or complexity.

- MUCAD is not appropriate if the time to plan, organize, and administer the MUCAD team exceeds the time for one client to complete the CAD design. This assumes that design specifications are clear, that the part complexity does not require design or manufacturing engagement of other technical specialists, or the MUCAD session is not intended as a training session.

- By analyzing the type of part to be modeled, we can predict the optimal number of users.

- Use of MUCAD teams significantly improves the ability to predict how much time a part will take to model compared to using single user CAD (see figure 4.8).

8.2.2 Profile and Team Formation System

Having a profile and team formation system helps a team to maximize its potential productivity. As seen in the examples, including from the AerosPACE program, several different methods of maximizing productivity using a profile and team formation system are possible. These include allowing managers to manually sort through profile data, using a genetic (or other) algorithm to automatically form the teams according to inputs generated by a manager, or allowing team leaders or even team members to organize themselves using data from the system and semi-automated software tools. These tools greatly enhance users' ability to overcome impediments common to virtual teams when attempting to maximize potential performance.

A commercial-grade tool could enable users to choose from among these three possibilities at their own discretion, all while providing automatically updated data about individual skills, experiences, and more from a variety of sources. The fact that this system could harvest and update most of the data in each profile automatically is important. As NASA learned the hard way, systems meant to enhance effectiveness by building a shared mental model, but do so in cumbersome ways that depend heavily on users manually inputting the information often fail [149]. A profile and team formation system, as proposed, should simply provide the data for managers and regular members of engineering design organizations, especially the increasing number which use virtual teams to get their work done. Then, without anyone having to do any data gathering work, a manager of an international organization can quickly and easily filter users to find just those who have, for example, 300 or more hours of experience using the Siemens NX sheet-metal design environment, speak Spanish, have high peer-rated social skills, and are available Wednesdays at 2 PM Pacific time for a weekly conference call.

Important opportunities beyond forming teams also exist once the flow of data into the system has been established. Users could be flagged for training or mentorships based on indicators triggered by their experiential data. Users themselves would be empowered to analyze their own profiles and improve their qualifications. Organizations could erect "Project Marketplaces" where managers can post projects with their requirements. System users could then be automatically notified or search on their own for projects within their organization for which they have both true passion and skill. What organization would not want to increase the opportunity for its members to work on projects for which they have strong intrinsic interest? Managers wishing to enable expert to novice knowledge transfer could more easily identify mentors with the right experiences and novices with the right motivation and interests to absorb experts' knowledge and skills. It is also very feasible that the system could have the right intelligence built in to enable it to suggest such relationships to managers, thus accelerating knowledge acquisition even further. In every case, including beyond just engineering design teams in other socio-technical systems, such a system will empower those with initiative to connect with, learn from, and accomplish with others.

It is my hope that the principles described in this research help to establish the potential and some of the fundamentals for such a system.

Principles

Principles derived from this portion of the work include:

- Using a structured method of forming teams and sub-teams to optimize the complement of fundamental area skills improves potential team productivity.
- Methods for complementary team formation can be enhanced and automated, either with an algorithm or a semi-automated tool.

8.3 Minimizing Process Losses

In order to minimize the $Losses_{pcs}$ virtual teams of engineering designers often experience, especially when working with MU tools, I investigated two important areas: 1) the strategies teams that wish to minimize these types of losses should employ to do so, and 2) the development of new types of tools to enable them to overcome the communication overheads inherent with their geographic distance.

8.3.1 Effective Virtual Multi-User Strategies

A Proposed Model of Virtual Engineering Design Team Collaboration

Virtual teams of design engineers face significant challenges, not only in learning all that's necessary to complete their projects, but in learning more about what Dym calls the "languages" and "arts" of engineering [85]. This research attempted to identify, through a review of the related literature and the experience of the authors with several years of multi-university, multi-disciplinary capstone projects, which remote collaboration tools tend to help student teams the most at different stages of product development. By following the recommended pattern, student virtual design teams will improve their efficiency and productivity during design and manufacturing projects.

We have found that each stage of the product development process has unique needs that should be responded to with specific tools. Table 8.1 shows a summary of which tools we recommend should be given extra consideration during each stage. We recognize that there are different circumstances that merit divergence from the proposed pattern, but assert that the pattern given provides a general outline upon which teams should base their communication.

During the Early Stages, teams will benefit most by holding a "kickoff meeting" or something similar at the beginning of the team formation process. Once face-to-face meetings become impractical, web conferencing, video conferencing and shared virtual annotation and drawing tools should be used to help further the development of the team relationship and generate ideas. During the Middle Stages, the team should transition to web conferencing, email, and shared databases to help give permanence to the design decisions as they become final. During the Late Stages, the team should rely more heavily on text messaging and social media to verify design values and give

Table 8.1: A summary of the recommended tools for each set of stages of the design process

Tool	Early Stages	Middle Stages	Late Stages
Face to Face (F2F)	x		x
Phone Call (1 to 1)			
Teleconference (x to x)		x	
Voice Mail			
Text messaging / Instant messaging		x	x
Web Conferences	x	x	
Video Conferencing	x		
Email		x	
Wikis			
Shared Virtual Annotation and Drawing Tools (Telestrator, NXConnect, awwap.com, etc.)	x	x	
Shared Data Editing (Google Drive, ShareLatex)		x	x

updates on manufacturing progress. Where possible, teams should also meet face-to-face in the Late Stages to integrate the several components into the final product.

Lessons Learned from A Multi-User Modeling Competition and the Taxonomy Experiments

We learned that an additional manner in which MUCAD teams can minimize their process losses, and even overcome apparent disadvantages, is through the way in which they, especially the leaders of MUCAD teams, communicate and collaborate with each other. Teams with proactive, positive strategies and communication styles performed better than other teams, including even, teams that were more experienced. As well, one strategy that teams in the Taxonomy experiments demonstrated which appeared to be generally effective was "rough-trunking" the first feature in the feature dependency tree in order to minimize the amount of time teammates waited to begin their work.

Principles

Principles derived from this portion of the work include:

- MUCAD teams can minimize process losses by using specific collaboration tools and methods at different points in the product development process.
- Negative communication styles among MUCAD teammates, and especially by team leaders increases process losses.
- Ability process losses such as domination and evaluation apprehension may play a major role in MUCAD teams where teammates have varying skill levels.
- Strategies such as "Rough Trunking" may reduce process losses for MUCAD teams.
- Too much communication may indicate a poorly developed shared mental model or other process losses in a MUCAD team.

8.3.2 Implementation of Novel Tools

The results of both laboratory experiments and a case study indicate that members of virtual, geographically distributed engineering design teams feel they can benefit significantly from using a CSA tool like the Telestrator, especially in the early stages of the design process. With industry and academia increasingly turning to geographically distributed, multi-disciplinary engineering design teams, CSA tools with characteristics similar to those of the Telestrator could become mainstays to help engineering designers communicate visual ideas effectively while making it easier for all team members to contribute. Overcoming this communication overhead can make a large difference in enabling virtual design team effectiveness.

Principles

Principles derived from this portion of the work include:

- By using a CSA such as the Telestrator, virtual engineering design teams can enhance the development of shared mental models and reduce process losses.

- Using a CSA can help teammates feel their contributions are more equal, potentially reducing ability process losses such as domination.

8.4 Future Work

Various areas that could be researched further in the future have been identified throughout the course of this work and are described here:

- Development of an automated method for classifying parts according to the taxonomy developed
- Additional testing to strengthen the predictive power of the models described for identifying the optimal number of MU team members
  - Iterating on the same parts and team sizes
  - Testing additional parts
  - Testing additional team sizes
  - Examining the time needed to organize a MUCAD team compared to the time needed for a single user to complete the model, especially for small parts
  - Examining the average time necessary to complete each standard feature type, thus enabling a more nuanced feature dependency tree model that takes into account the varying complexity of different feature types
- The implications and effectiveness of MU teams attempting to “multi-trunk” a part
- A more refined iteration of the Profile and Team Formation system, perhaps pilot tested in an industry setting
- Additional novel MU tools and iterative improvements on existing ones
  - An improved version of the Telestrator that is more tightly integrated with NXConnect or another MUCAD system
  - An improved version of the integrated task list [106] that is more tightly integrated with NXConnect or another MUCAD system

- A tool that is integrated into a MUCAD system to allow MU team members a live view of each of their teammates' MUCAD windows, as desired, enabling them to converse and collaborate better in context.
- A feature in a MUCAD system which allows a user to view only his/her additions to the part while continuing to work, in order to avoid distraction and focus on one's own work
- A tool that allows managers and team members to graphically observe their current position in a project or assembly as well as their other teammates' positions along with data such as the number of man-hours spent on each part, sub-assembly, or assembly

- Investigation of how modeling techniques change from single user to MU settings

REFERENCES

[1] Red, E., French, D., Jensen, G., Walker, S. S., and Madsen, P., 2013. "Emerging Design Methods and Tools in Collaborative Product Development". *Journal of Computing and Information Science in Engineering,* **13**(3), apr, p. 031001. 1, 6, 36

[2] French, D. J., Red, W. E., Walker, S. S., Madsen, P., Jensen, C. G., Robinson, D., Ruchty, J., Ward, S., Sanchez, C., and Phelps, G., 2012. e - Handbook Summary Report. 1

[3] Wilczynski, V., and Jennings, J., 2003. "Creating virtual teams for engineering design". *International Journal of Engineering Education,* **19**(2), pp. 316–327. 1

[4] Moore, B., Rhodes, M., and Stanley, R., 2011. Telework 2011 A WorldatWork Special Report. Tech. rep., The Total Rewards Association and Direringer Research Group Inc. 1, 5

[5] Katz, A., and Te'eni, D., 2007. "The contingent impact of contextualization on computer-mediated collaboration". *Organization Science,* **18**(2), mar, pp. 261–279. 1, 37

[6] Calantone, R., and Di Benedetto, C., 2000. "Performance and time to market: accelerating cycle time with overlapping stages". *IEEE Transactions on Engineering Management,* **47**(2), may, pp. 232–244. 1

[7] Red, E., Holyoak, V., Jensen, C. G., Marshall, F., Ryskamp, J., and Xu, Y., 2010. "CAx : A Research Agenda for Collaborative Computer-Aided Applications". *Computer-Aided Design,* **7**, pp. 1–18. 1, 6, 36

[8] Onshape, 2015. Onshape. https://www.onshape.com/. 1, 6, 36

[9] Levi, D., 2014. *Group Dynamics for Teams*, 4 ed. Sage Publications, Thousand Oaks, California. 1, 2, 7, 25, 30, 31, 64, 101, 112, 121

[10] Driskell, J., Radtke, P., and Salas, E., 2003. "Virtual teams: effects of technological mediation on team performance.". *Group Dynamics: Theory, Research, and Practice,* **7**(4), pp. 297–323. 1, 5, 7, 30

[11] MacMillan, J., Entin, E., and Serfaty, D., 2004. "Communication overhead: The hidden cost of team cognition". In *Team Cognition: Understanding the factors that drive process and performance*. pp. 61–82. 1, 19, 25, 27, 29, 64, 112

[12] Grimshaw, D. J., Kwok, F. S., Igbaria, M., and Tan, M., 1998. "The Business Benefits of the Virtual Organization". In *The Virtual Workplace*. Idea Group Publishing, Hershey, PA, ch. 3, pp. 45–71. 2

[13] Moreland, R. L., Argote, L., and Krishnan, R., 1996. “Socially Shared Cognition at Work”. In *What’s Social About Social Cognition?*, J. L. Nye and A. M. Brower, eds. Sage Publications, Thousand Oaks, California, ch. 3, pp. 57–87. 2, 19, 25, 27, 28, 120

[14] Bercovitz, J., and Feldman, M., 2011. “The mechanisms of collaboration in inventive teams: Composition, social networks, and geography”. *Research Policy,* **40**(1), feb, pp. 81–93. 2

[15] Berry, G. R., 2011. “Enhancing Effectiveness on Virtual Teams: Understanding Why Traditional Team Skills Are Insufficient”. *Journal of Business Communication,* **48**(2), feb, pp. 186–206. 2, 8

[16] Parker, G. M., 2003. *Cross-Functional Teams: Working with Allies, enemies, and other strangers*, 2nd ed. Jossey-Bass, San Francisco. 2, 18, 29, 54, 91, 97, 101

[17] Petkovic, D., 2010. “Work in progresse-TAT: Online tool for teamwork and soft skills assessment in software engineering education”. In 40th ASEE/IEEE Frontiers in Education Conference, pp. 26–28. 2

[18] Lingard, R., and Barkataki, S., 2011. “Teaching teamwork in engineering and computer science”. *41st ASEE/IEEE Frontiers in Education Conference*, pp. 1–5. 2

[19] Kirkpatrick, A. T., Danielson, S., Warrington, R. O., Smith, R. N., Thole, K. A., Wepfer, W. J., and Perry, T., 2011. “Vision 2030 Creating the Future of Mechanical Engineering Education”. In Proceedings of the ASEE International Conference and Exposition, no. December, pp. AC 2011–2804. 2, 37

[20] Steiner, I. D., 1972. *Group Process and Productivity*, 8 ed. Academic Press, New York. 2, 51

[21] Kravitz, D., and Martin, B., 1986. Ringelmann Rediscovered: The Original Article. 3

[22] Mejias, R. J., 2007. “The Interaction of Process Losses, Process Gains, and Meeting Satisfaction Within Technology-Supported Environments”. *Small Group Research,* **38**(1), pp. 156–194. 3, 97

[23] Brooks, F., 1975. *The mythical man-month*, Vol. 10. Addison Wesley 1995. 4, 19, 26, 52

[24] Staats, B. R., Milkman, K. L., and Fox, C. R., 2012. “The team scaling fallacy: Underestimating the declining efficiency of larger teams”. *Organizational Behavior and Human Decision Processes,* **118**(2), pp. 132–142. 4

[25] Golden, T. D., and Raghuram, S., 2010. “Teleworker knowledge sharing and the role of altered relational and technological”. *Journal of Organizational Behavior,* **1085**(June 2009), pp. 1061–1085. 5, 123

[26] Hertel, G., Geister, S., and Konradt, U., 2005. “Managing virtual teams: A review of current empirical research”. *Human Resource Management Review,* **15**(1), mar, pp. 69–95. 5, 7, 8

[27] Salomo, S., Keinschmidt, E. J., and De Brentani, U., 2010. “Managing new product development teams in a globally dispersed NPD program”. In Journal of Product Innovation Management, Vol. 27, pp. 955–971. 5

[28] Chinowsky, P. S., and Rojas, E. M., 2003. "Virtual Teams: Guide to Successful Implementation". *Journal of Management in Engineering,* **19**(3), pp. 98–106. 5

[29] May, A., and Carter, C., 2001. "A case study of virtual team working in the European automotive industry". *International Journal of Industrial Ergonomics,* **27**(3), mar, pp. 171–186. 5

[30] Stough, S., Eom, S., and Buckenmyer, J., 2000. "Virtual teaming: a strategy for moving your organization into the new millennium". *Industrial Management & Data Systems,* **100**(8), pp. 370–378. 5

[31] Peterson, K., 2011. "A Wing and a Prayer: Outsourcing at Boeing". *Reuters*(January), pp. 1–12. 5

[32] Fox, W. M., 1995. "from the SAGE Social Science Collections . All Rights Reserved .". *Journal of Applied Behavioral Science,* **31**(1), pp. 91–105. 6

[33] French, D. J., Red, W. E., Walker, S. S., Madsen, P., Jensen, C. G., Robinson, D., Ruchty, J., Ward, S., and Sanchez, C. e-Handbook of Collaborative Engineering. 6, 30, 38

[34] Red, E., Jensen, G., French, D., and Weerakoon, P., 2011. "Multi-user architectures for computer-aided engineering collaboration". In Proceedings of the 2011 17th International Conference on Concurrent Enterprising (ICE 2011), IEEE, pp. 1–10. 6, 36

[35] Briggs, J. C., Hepworth, A. I., Stone, B. R., Coburn, J. Q., Jensen, C. G., and Red, E., 2015. "Integrated, Synchronous Multi-user Design and Analysis". *Journal of Computing and Information Science in Engineering*. 6

[36] Weerakoon, P., 2013. "A Networking Architecture for a Multi-User FEA Pre-Processor". *Computer-Aided Design and Applications,* **10**(3), may, pp. 527–540. 6

[37] Richey, M., Zender, F., Schrage, D., Jensen, G., Fehr, J., Symmonds, M. M., French, D. E., and McPherson, B., 2012. "An innovative approach to an integrated design and manufacturing multi-site cloud-based capstone project". *ASEE Annual Conference & Exposition*. 6

[38] Google, 2016. Google Docs. https://www.google.com/docs/about/. 6

[39] Dyer, W. G. J., Dyer, J. H., and Dyer, W. G., 2013. *Team Building*, 5 ed. Jossey-Bass, San Francisco. 7, 8, 18, 22, 54

[40] Parks, C. D., and Sanna, L. J., 1998. *Group Performance And Interaction*. Westview Press. 7

[41] de Pillis, E., and Furumo, K., 2015. "Virtual vs. Face-to-Face Teams: Deadbeats, Deserters, and Other Considerations". *International Journal of Business and Information,* **10**(3), pp. 318–320. 7

[42] French, D. J., Stone, B., Nysetvold, T. T., Hepworth, A., and Red, W. E., 2014. "COLLABORATIVE DESIGN PRINCIPLES FROM MINECRAFT WITH APPLICATIONS TO

MULTI-USER CAD". In Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, pp. 1–14. 8, 38, 142, 147

[43] Bariso, J., 2016. "Emotional Intelligence 101 : Why a Millennial ' s Letter to Yelp ' s CEO Got Her Fired". *Inc.*, pp. 1–9. 8

[44] Nazar, J., 2016. "20 Things 20 Year Olds Don ' t Get". *Forbes. Forbes Magazine*(753), pp. 1–12. 8

[45] Sonnert, G., and Fox, M. F., 2012. "Women, Men, and Academic Performance in Science and Engineering: The Gender Difference in Undergraduate Grade Point Averages". *The Journal of Higher Education,* **83**(1), pp. 73–101. 11

[46] Hackman, J., 1987. "The design of work teams". *Handbook of Organizational Behavior*, pp. 315–342. 18, 19, 64, 86, 124

[47] Hackman, J. R., 2009. "Why Teams Don't Work". *Harvard Business Review*, pp. 3–9. 18, 121

[48] Hepworth, A., DeFigueiredo, B., Shumway, D., Fronk, N., and Jensen, C. G., 2014. "Semantic Conflict Reduction Through Automated Feature Reservation in Multi-User Computer-Aided Design". *2014 International Conference on Collaboration Technologies and Systems (CTS)*, pp. 56–63. 18, 19, 52

[49] MacMillan, J., and Paley, M., 2002. "Designing the best team for the task: Optimal organizational structures for military missions". *New Trends in Cooperative Activities: System Dynamics in Complex Settings.* 19, 21, 27, 28

[50] Layton, R. A., Loughry, M. L., Ohland, M. W., and Ricco, G. D., 2010. "Design and validation of a web-based system for assigning members to teams using instructor-specified criteria". *Advances in Engineering Education,* **2**(1), pp. 1–28. 19, 21

[51] Espinosa, J., Kraut, R., and Slaughter, S., 2002. "Shared Mental Models, Familiarity and Coordination: A Mulit-Method Study of Distributed Software Teams". In International Conference for Information Systems, ICIS. 19, 25, 27, 28, 29, 112

[52] Kramer, R. M., and Tyler, T. R., 1996. *Trust in Organizations*. Sage Publications. 20, 29

[53] Woolley, A. W., Hackman, J. R., Jerde, T. E., Chabris, C. F., Bennett, S. L., and Kosslyn, S. M., 2007. "Using brain-based measures to compose teams: how individual capabilities and team collaboration strategies jointly shape performance". *Social Neuroscience,* **2**(2), jan, pp. 96–105. 20, 25

[54] Futwiz, 2014. I Am Lazy. http://www.futwiz.com/en/iamlazy. 20

[55] Katz, E. M., 2014. "Bounce Back From Rejection". *Happen.* 20

[56] MYAI, 2014. Action and Influence. http://myai.org/. 20

[57] Silva, F., and Flavia, M. S., 2010. “Team Composer: Assembling groups through social matching”. In Proceedings of the 2010 14th International Conference on Computer Supported Cooperative Work in Design, pp. 128–133. 21

[58] LaFasto, F., and Larson, C., 2001. *When Teams Work Best: 6,000 team members and leaders tell what it takes to succeed*. Sage Publications, Thousand Oaks, California. 23

[59] Naikar, N., Pearce, B., Drumm, D., and Sanderson, P. M., 2003. “Designing Teams for First-of-a-Kind, Complex Systems Using the Initial Phases of Cognitive Work Analysis: Case Study”. *Human Factors: The Journal of the Human Factors and Ergonomics Society,* **45**(2), pp. 202–217. 23, 24, 98

[60] Guay, R. B., 1976. Purdue Spatial Visualization Tests - Visualization of Rotations. 24, 65

[61] Gimmestad, B., 1990. “Gender differences in spatial visualization and predictors of success in an engineering design course”. In Proceedings of the National Conference on Women in Mathematics and the Sciences, no. 801, pp. 133–136. 24

[62] Hamlin, A., Boersma, N., and Sorby, S., 2006. “Do Spatial Abilities Impact the Learning of 3-D Solid Modeling Software ?”. *American Society for Engineering Education*. 24

[63] Sorby, S., 2009. “Developing 3-D spatial visualization skills”. *Engineering Design Graphics Journal*. 24

[64] Yoon, S., 2011. Revised Purdue Spatial Visualization Test: Visualization of Rotations (Revised PSVT:R). 24

[65] Koster, J., Velazco, A., and Munz, C., 2012. “HYPERION UAV: An International Collaboration”. In 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, no. January, pp. 1–23. 24, 29, 112, 119, 121, 124

[66] Sauer, S., and Arce, P., 2004. “Team Member Selection: A Functional-Based Approach”. In Proceedings of the 2004 ASEE Annual Conference & Exposition. 24, 62, 71

[67] Woolley, a. W., Gerbasi, M. E., Chabris, C. F., Kosslyn, S. M., and Hackman, J. R., 2008. “Bringing in the Experts: How Team Composition and Collaborative Planning Jointly Shape Analytic Effectiveness”. *Small Group Research,* **39**(3), pp. 352–371. 24, 28

[68] Suchan, J., and Hayzak, G., 2001. “The communication characteristics of virtual teams: a case study”. *IEEE Transactions on Professional Communication,* **44**(3), pp. 174–186. 24

[69] Liang, D. W., Moreland, R., and Argote, L., 1995. “Group Versus Individual Training and Group Performance: The Mediating Role of Transactive Memory”. *Personality and Social Psychology Bulletin,* **21**(4), apr, pp. 384–393. 25, 28

[70] Faraj, S., and Sproull, L., 2000. “Coordinating expertise in software development teams”. *Management Science,* **46**(12), pp. 1554–1568. 25, 28

[71] di Penta, M., Harman, M., Antoniol, G., Qureshi, F., Penta, M. D., and Harman, M., 2007. “The Effect of Communication Overhead on Software Maintenance Project Staffing: a

Search-Based Approach". *2007 IEEE International Conference on Software Maintenance*, oct, pp. 315–324. 25

[72] Hepworth, A., Halterman, K., Stone, B., Yarn, J., and Jensen, C. G., 2015. "An Integrated Task Management System to Reduce Semantic Conflicts in Multi-user CAD". *Concurrent Engineering: Research and Applications*(March), pp. 1–12. 25, 27, 28, 36, 124

[73] Erickson, T., and Gratton, L., 2007. "Eight ways to build collaborative teams". *Harvard Business Review*. 25, 101

[74] Swaab, R. I., Schaerer, M., Anicich, E. M., Ronay, R., and Galinsky, A. D., 2014. "The Too-Much-Talent Effect: Team Interdependence Determines When More Talent Is Too Much or Not Enough.". *Psychological Science*. 26, 102

[75] Schippers, M., Homan, A. C., and Van Knippenberg, D., 2013. "To reflect or not to reflect: Prior team performance as a boundary condition of the effects of reflexivity on learning and final team performance". *Journal of Organizational Behavior,* **23**(February 2012), pp. 6–23. 29

[76] Stempfle, J., and Badke-Schaub, P., 2002. "Thinking in design teams-an analysis of team communication". *Design Studies,* **23**, pp. 473–496. 29, 112

[77] Thamhain, H., and Wilemon, D., 1987. "Building high performing engineering project teams". *Engineering Management, IEEE Transactions*(3), pp. 130–137. 29, 112

[78] Zaccaro, S. J., Rittman, A. L., and Marks, M. a., 2001. "Team leadership". *The Leadership Quarterly,* **12**(4), pp. 451–483. 29, 112

[79] Edmondson, A. C., 2003. "Speaking Up in the Operating Room : How Team Leaders Promote Learning in Interdisciplinary Action Teams". *Journal of Management Studies,* **40**(September), pp. 1419–1452. 30, 113, 114

[80] Maruping, L. M., and Agarwal, R., 2004. "Managing team interpersonal processes through technology: a task-technology fit perspective.". *The Journal of applied psychology,* **89**(6), pp. 975–990. 30, 119, 128

[81] Daft, R., and Lengel, R., 1986. "Organizational information requirements, media richness and structural design". *Management Science,* **32**(5), pp. 554–571. 30

[82] Maznevski, M. L., and Chudoba, K. M., 2000. "Bridging Space Over Time: Global Virtual Team Dynamics and Effectiveness". *Organization Science,* **11**(5), pp. 473–492. 30, 124

[83] Levi, D., and Rinzel, L., 1998. "Employee attitudes toward various communications technologies when used for communicating about organizational change". In *Human Factors in organizational designand management*, P. Vink, E. Koningsveld, and S. Dhondt, eds., 6 ed. Elsevier, Amsterdam, pp. 483–488. 30

[84] Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., and Leifer, L. J., 2005. "Engineering Design Thinking, Teaching, and Learning". *Journal of Engineering Education*(January), pp. 103–120. 31, 36

[85] Dym, C. L., 1999. "Learning Engineering: Design, Languages, and Experiences". *Journal of Engineering Education*(April), pp. 145–148. 31, 36, 156

[86] Crichton, D., 2015. "After 3 Years And $64M In Seed Funding, Onsape Launches The Mother of all Products". *Tech Crunch*, pp. 1–8. 36

[87] Polar Services Company, R., 2005. Design Procedures. 36

[88] Sachse, P., Ro, A., and Schu, M., 2003. "Support value of sketching in the design process". *Research in Engineering Design,* **14**(2), pp. 89–97. 36, 37, 133

[89] Ullman, D. G., Wood, S., and Craig, D., 1990. "The importance of drawing in the mechanical design process". *Computers & Graphics,* **14**(2), jan, pp. 263–274. 36, 37

[90] Do, E. Y. L., Gross, M. D., Neiman, B., and Zimring, C., 2000. "Intentions in and relations among design drawings". *Design Studies,* **21**(5), pp. 483–503. 36

[91] Akin, Ö., and Lin, C., 1995. "Design protocol data and novel design decisions". *Design Studies,* **16**(2), pp. 211–236. 36

[92] Bellamy, R., Desmond, M., Martino, J., Matchen, P., Ossher, H., Richards, J., and Swart, C., 2011. "Sketching tools for ideation: NIER track". *2011 33rd International Conference on Software Engineering (ICSE)*, pp. 808–811. 37, 40

[93] Glier, M., and Schmidt, S., 2011. "Distributed ideation: Idea generation in distributed capstone engineering design teams". *International Journal of Engineering Education,* **27**(6), pp. 1281–1294. 37

[94] Bentley, R., Rodden, T., Sawyer, P., and Sommerville, I., 1994. "Architectural support for cooperative multiuser interfaces". *Computer,* **27**(5), may, pp. 37–46. 37

[95] Chandrasegaran, S., Badam, S. K., Zhao, Z., Elmqvist, N., Kisselburgh, L., and Ramani, K., 2014. "Collaborative Sketching with skWIKI: A Case Study". In Proceeding of the ASME 2014 IDETC/CIE Conference, pp. 1–10. 37, 40, 122, 133, 142

[96] Hailpern, J., Hinterbichler, E., Leppert, C., Cook, D., and Bailey, B., 2007. "TEAM STORM: Demonstrating an interaction model for working with multiple ideas during creative group work". *Proceedings of the Conference on Creativity & Cognition*, pp. 193–202. 37

[97] Sangiorgi, U. B., Beuvens, F., and Vanderdonckt, J., 2012. "User interface design by collaborative sketching". *Proceedings of the Designing Interactive Systems Conference on - DIS '12*, p. 378. 38

[98] Jonson, B., 2005. "Design ideation: the conceptual sketch in the digital age". *Design Studies,* **26**(6), pp. 613–624. 38

[99] Lang, S., Dickinson, J., and Buchal, R., 2002. "An overview of cognitive factors in distributed design". *Proceedings of the Sixth Conference on Computer Supported Cooperative Work in Design,* **48**, pp. 190–197. 38

[100] GoodCode. A Web Whiteboard App. https://awwapp.com/. 40

[101] Borrego, M., Douglas, E. P., and Amelink, C. T., 2009. "Quantitative, qualitative, and mixed research methods in engineering education". *Journal of Engineering Education*(January). 43

[102] Crowson, R. A., 1972. *Classification and biology*. 44

[103] Steinmetz, M., and Navarro, J. F., 2002. "The Hierarchical Origin of Galaxy Morphologies". pp. 1–9. 44

[104] Gideon, J. M., Dagli, C. H., and Miller, A., 2005. "Taxonomy of Systems-of-Systems". *Institute of Electrical and Electronics Engineers IEEE*(JANUARY 2005), pp. 356–363. 44

[105] Todd, R. H., Allen, D. K., and Alting, L., 1994. *Fundamental Principles of Manufacturing Processes*, 1 ed. Industrial Press Inc., New York, New York, USA. 44

[106] Hepworth, A. I., Tew, K., Nysetvold, T., Bennett, M., and Greg Jensen, C., 2014. "Automated Conflict Avoidance in Multi-user CAD". *Computer-Aided Design and Applications,* **11**(February 2015), pp. 141–152. 45, 159

[107] Alexandrov, N. M., Lewis, R. M., Gumbert, C. R., Green, L. L., and Newman, P. a., 2001. "Approximation and Model Management in Aerodynamic Optimization with Variable-Fidelity Models". *Journal of Aircraft,* **38**(6), pp. 1093–1101. 49

[108] West, D., 2001. *Introduction to Graph Theory*, volume 2 ed. Upper Saddle River: Prentice Hall. 50

[109] Moynihan, L. M., and Peterson, R. S., 2001. "A contingent configuration approach to understanding the role of personality in organizational groups". *Research in Organizational Behavior,* **23**, pp. 327–378. 51

[110] Page, E., 2004. "The Rate of Team Performance Change Over Time". PhD thesis, Georgia Institute of Technology. 51

[111] Nelson, D., Lehninger, A., and Cox, M., 2008. *Lehninger Principles of Biochemistry*. W. H. Freeman. 54

[112] Brannick, M. T., Salas, E., and Prince, C., 2009. *Team Performance Assessment and Measurement - Theory, Methods, and Applications*. Taylor & Francis, Mahwah, New Jersey. 64

[113] Lin, C., Standing, C., and Liu, Y. C., 2008. "A model to develop effective virtual teams". *Decision Support Systems,* **45**(4), pp. 1031–1045. 64

[114] Hertel, G., Konradt, U., and Voss, K., 2006. "Competencies for virtual teamwork: Development and validation of a web-based selection tool for members of distributed teams". *European Journal of Work and Organizational Psychology,* **15**(4), pp. 477–504. 64, 120

[115] Kaufman, D. B., Felder, R. M., and Fuller, H., 2000. "Accounting for individual effort in cooperative learning teams". *Journal of Engineering Education*(April), pp. 133–140. 65

[116] Ohland, M. W., Loughry, M. L., Woehr, D. J., Bullard, L. G., Finelli, C. J., Layton, R. A., Pomeranz, H. R., and Shmucker, D. G., 2012. "The comprehensive assessment of team member effectiveness: Development of a behaviorally anchored rating scale for self and peer evaluation". *Academy of Management Learning & Education,* **11**(4), aug, pp. 609–630. 73

[117] Tuckman, B., 1965. "Developmental Sequence In Small Groups". *Psychological Bulletin,* **63**(6), pp. 384–399. 74

[118] Dallal, G. E. "Multiple Comparisons". In *The Little Handbook of Statistical Practice*, 1.1 ed. Amazon, ch. Analysis o. 74

[119] Feltz, D. L., Short, S. E., and Joseph, P., 2008. "Efficacy Beliefs of Teams". In *Self-Efficacy in Sport*, illustrate ed. Human Kinetics, ch. 4. 77

[120] Artinger, L., Clapham, L., Hunt, C., and Meigs, M., 2006. "The social benefits of intramural sports". *Naspa Journal,* **43**(1), pp. 69–86. 82

[121] Barcelona, B., 2002. "Student involvement in campus recreational sports activities and gains in team-functioning.". ... *The Cyber Journal of Applied Leisure and Recreation ...* (March 2002), pp. 1–13. 82

[122] Stevens, M., and Campion, M., 1999. "Staffing work teams: Development and validation of a selection test for teamwork settings". *Journal of Management,* **25**(2), pp. 207–228. 86

[123] Ross, J. A., 2006. Trust Makes the Team Go 'Round. Tech. rep., Harvard Business School. 91

[124] Mangalindan, J., 2012. "Amazon's recommendation secret". *CNN Money - Fortune Tech*, pp. 2012–2015. 94

[125] Littlepage, G., Robison, W., and Reddington, K., 1997. "Effects of Task Experience and Group Experience on Group Performance, Member Ability, and Recognition of Expertise". *Organizational Behavior and Human Decision Processes,* **69**(2), pp. 133–147. 97

[126] Inc, S. I. JMP version 11. http://www.jmp.com/support/notes/35/282.html. 99

[127] Morgan, E., Gunes, H., and Bryan-Kinns, N., 2015. "Using affective and behavioural sensors to explore aspects of collaborative music making". *International Journal of Human-Computer Studies,* **82**, pp. 31–47. 101

[128] Dieter, G. E., and Schmidt, L. C., 2009. *Engineering Design*. McGraw-Hill Higher Education, New York City. 118, 119, 122

[129] National Aeronautics and Space Administration, 1994. *System Engineering Toolbox for Design-Oriented*. No. December. 118

[130] Siebdrat, F., Hoegl, M., and Ernst, H., 2009. "How to Manage Virtual Teams". *MIT Sloan Management Review,* **50**, pp. 63–68. 120

[131] Lovelace, K., Shapiro, D. L., and Weingart, L. R., 2001. "Maximizing cross-functional new product teams' innovativeness and constraint adherence: A conflict communications perspective". *Academy of Management Journal,* **44**(4), pp. 779–793. 120

[132] Yang, M. C., 2009. "Observations on concept generation and sketching in engineering design". *Research in Engineering Design,* **20**(1), dec, pp. 1–11. 122

[133] Kopp, G., 1999. "Engineering graphics in the new millennium: integrating the strengths of sketching and CAD". In Frontiers in Education Conference, 1999., pp. 12–13. 122

[134] Lang, J., Cruse, S., McVey, F. D., and McMasters, J., 1999. "Industry expectations of new engineers: A survey to assist curriculum designers". *Journal of Engineering Education*(January). 122

[135] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.-H., 2007. *Engineering Design*, 3rd ed. Springer-Verlag, London. 122

[136] Doerry, E., Klempous, R., Nikodem, J., and Paetzold, W., 2004. "Virtual student exchange: Lessons learned in virtual international teaming in interdisciplinary design education". *Ithet 2004: Proceedings of the Fifth International Conference on Information Technology Based Higher Education and Training*, pp. 650–655\r676. 123

[137] Bracewell, R. H., Ahmed, S., and Wallace, K. M., 2004. "Dred and Design Folders, a Way of Capturing, Storing and Passing on, knowledge generated during design projects". In DETC04, ASME 2004 Design Engineering Technical Conferences, no. 1970, pp. 1–12. 124

[138] Klein, M., 1993. "Capturing design rationale in concurrent engineering teams". *IEEE Computer Journal,* **26**(Special Issue on Computer Support for Concurrent Engineering), pp. 1–17. 124

[139] Hinds, P. J., and Bailey, D. E., 2003. "Out of Sight, Out of Sync: Understanding Conflict in Distributed Teams". *Organization Science,* **14**(6), pp. 615–632. 128, 129

[140] Jehn, K. a., and Mannix, E. a., 2001. "The dynamic nature of conflict: A longitudinal study of intragroup conflict and group performance". *Academy of Management Journal,* **44**(2), pp. 238–251. 128

[141] Mikhail, S., 2009. "Decision Making Process for Implementing DFMA at IGT". In International forum on DFMA. 128

[142] Grinter, R. E., Herbsleb, J. D., and Perry, D. E., 1999. "The Geography of Coordination : Dealing with Distance in R&D Work". *Proceedings of the ACM Conference on Supporting Group Work*, pp. 306–315. 129

[143] Worinkeng, E., Summers, J. D., and Joshi, S., 2013. "Can a Pre-sketching Activity Improve Idea Generation?". *Smart Product Engineering,* **5**, pp. 583–592. 136, 137

[144] Bokonyi, S., and Hinton, B. L., 1968. "Environmental Frustration and Creative Problem Solving". *Journal of Applied Psychology,* **52**(3), pp. 211–217. 140

[145] Taylor, A. D., 2009. Multiple-Comparison Procedures. 140

[146] Cannon, L., Cunningham, C. C., Inouye, A. L., Stone, B., and Zender, F., 2015. “Looking back : A Student Review and History of AerosPACE a Multi- Looking back : A Student Review and History of AerosPACE a Multi-University , Multi-Disciplinary , Distributed , Industry-University Capstone Project”. In 122nd ASEE Annual Conference & Exposition. 144

[147] Gorrell, S., Jensen, C. G., Stone, B., Red, E., Richey, M., Zender, F., Wright, M., French, D., Hayashibara, S., Johnson, C., and John, S., 2014. “Aerospace Partners for the Advancement of Collaborative Engineering”. In 121st ASEE Annual Conference & Exposition. 144

[148] Zender, F., Schrage, D., Richey, M., and Black, A. “Wing Design as a Symphony of Geographically Dispersed, Multi-disciplinary, Undergraduate Students”. *arc.aiaa.org*. 144

[149] Martin, P. K., 2012. REVIEW OF NASAS LESSONS LEARNED INFORMATION SYSTEM. 154

APPENDIX A. APPENDIX A: GENETIC ALGORITHM SOURCE CODE

A.1 Genetic Algorithm Fitness Functions

A.1.1 Social Fitness Function

```
//unique team members?
        if (teamMembers.Distinct().Count() !=
           teamMembers.Count)
            isFeasable = false;
        int i = 0;
        int males = 0;
        int females = 0;
        while (i < teamMembers.Count)
        {
            if(teamMembers[i].gender == gender.male)
                males += 1;
            else
                females += 1;
            i++;
        }
        if(males < 1 || females < 1)
            isFeasable = false;
        if(males >= 2 && females >= 2)
            fitness = fitness + 0.25;
//Location / School
        int BYUstudents = 0;
```

```
int ERstudents = 0;
int GTstudents = 0;
int PDstudents = 0;
int UCLAstudents = 0;
foreach (teamMember member in teamMembers)
{
    if (member.location == location.BYU)
        BYUstudents += 1;
    else if(member.location == location.ER)
        ERstudents += 1;
    else if (member.location == location.GT)
        GTstudents += 1;
    else if (member.location == location.PD)
        PDstudents += 1;
    else if (member.location == location.UCLA)
        UCLAstudents += 1;
}
    {

    if(BYUstudents == 1 || ERstudents == 1 ||
       GTstudents == 1 || PDstudents == 1 ||
       UCLAstudents == 1)
        isFeasable = false;
    int schools = 0;
    if(BYUstudents >= 2)
        schools += 1;
    if(ERstudents >= 2)
        schools += 1;
    if(GTstudents >= 2)
        schools += 1;
```

```
            if(PDstudents >= 2)
                schools += 1;
            if(UCLAstudents >= 2)
                schools += 1;
            if(schools < 3)
                isFeasable = false;
             }

//Leadership
            List<teamMember> top4 =
               teamMembers.OrderByDescending(s =>
               s.leadership).ToList().GetRange(0, 4);
            double teamLeaderPercentile =
               top4[0].leadership;
        double teamViceLeaderPercentile =
           top4[1].leadership; //I want the leadership
           score the second person in the list...
            if(teamLeaderPercentile < .75 ||
               teamViceLeaderPercentile < .75)
                isFeasable = false;
            double IPTLead1Score = top4[2].leadership; //I
               want the leadership score of
```

```
    double IPTLead2Score = top4[3].leadership; //I
       want the leadership score of








//ensure there are enough leaders on the team:
fitness += (teamLeaderPercentile +
   teamViceLeaderPercentile + IPTLead1Score +
   IPTLead2Score)/4.0;
//ensure there are not too many leaders on the
   team:
double avgTeamLeadership = 0;
double totalTeamLeadership = 0;
 foreach(teamMember member in teamMembers)
{
    //this calculates the average level of
       leadership ability of the team
    totalTeamLeadership = totalTeamLeadership +
       member.leadershipRaw;
}
 avgTeamLeadership = totalTeamLeadership /
    teamMembers.Count();
if(avgTeamLeadership > 2)
    fitness += avgTeamLeadership*-0.5+2;
else
    fitness += avgTeamLeadership*0.5;
```

```
//Social Skill
        double avgTeamSocialSkill = 0;
        double totalTeamSocialSkill = 0;
        foreach(teamMember member in teamMembers)
        {
            //this calculates the average level of social
               skill of the team
            totalTeamSocialSkill = totalTeamSocialSkill +
               member.social;
        }
        avgTeamSocialSkill = totalTeamSocialSkill /
           teamMembers.Count();
        fitness += avgTeamSocialSkill*.25;
//Motivation
        double avgTeamMotivation = 0;
        double totalTeamMotivation = 0;
        foreach(teamMember member in teamMembers)
        {
            //this calculates the average level of
               motivation of the team
            totalTeamMotivation = totalTeamMotivation +
               member.motivation;
        }
        avgTeamMotivation = totalTeamMotivation /
           teamMembers.Count();
        fitness += avgTeamMotivation *.25;

        return new Tuple<double, bool>(fitness,
           isFeasable);
```

```
        }

\subsection{Technical Fitness Function}
        Tuple<double, bool> getTechnicalFitness()
        {
            double fitness = 0;
            bool isFeasable = true;

    //unique team members?
            if (teamMembers.Distinct().Count() !=
               teamMembers.Count)
                isFeasable = false;
    //Gender?
            int i = 0;
            int males = 0;
            int females = 0;
            while (i < teamMembers.Count)
            {
                if(teamMembers[i].gender == gender.male)
                    males += 1;
                else
                    females = females + 1;
                i++;
            }
            if(males < 1 || females < 1)
                isFeasable = false;

    //Location
            int BYUstudents = 0;
            int ERstudents = 0;
```

```
int GTstudents = 0;
int PDstudents = 0;
int UCLAstudents = 0;
foreach (teamMember member in teamMembers)
{
    if (member.location == location.BYU)
        BYUstudents += 1;
    else if (member.location == location.ER)
        ERstudents += 1;
    else if (member.location == location.GT)
        GTstudents += 1;
    else if (member.location == location.PD)
        PDstudents += 1;
    else if (member.location == location.UCLA)
        UCLAstudents += 1;
}
{

    if (BYUstudents == 1 || ERstudents == 1 ||
       GTstudents == 1 || PDstudents == 1 ||
       UCLAstudents == 1)
        isFeasable = false;
    //how many schools have at least two students
       on them? There need to be at least 3
       schools for the team to be feasible
    int schools = 0;
    if (BYUstudents >= 2)
        schools += 1;
    if (ERstudents >= 2)
        schools += 1;
```

```
            if (GTstudents >= 2)
                schools += 1;
            if (PDstudents >= 2)
                schools += 1;
            if (UCLAstudents >= 2)
                schools += 1;
            if (schools < 3)
                isFeasable = false;
        }

//Leadership

        List<teamMember> top4 =
           teamMembers.OrderByDescending(s =>
           s.leadership).ToList().GetRange(0, 4);
        double teamLeaderPercentile = top4[0].leadership;
        double teamViceLeaderPercentile =
           top4[1].leadership;
        if (teamLeaderPercentile < .75 ||
           teamViceLeaderPercentile < .75)
            isFeasable = false;

        //ensure there are enough leaders on the team:
        double IPTLead1Score = top4[2].leadership; //I
           want the leadership score of the teammate with
           the 3rd highest score
        double IPTLead2Score = top4[3].leadership; //I
           want the leadership score of the teammate with
           the 4th highest score
```

```
        fitness += (teamLeaderPercentile +
           teamViceLeaderPercentile + IPTLead1Score +
           IPTLead2Score) / 4.0;

        //ensure there are not too many leaders on the
           team:
        double avgTeamLeadership = 0;
        double totalTeamLeadership = 0;
        foreach (teamMember a in teamMembers)
        {
            totalTeamLeadership += a.leadershipRaw;
        }
        avgTeamLeadership = totalTeamLeadership /
           teamMembers.Count();

        if (avgTeamLeadership > 2)
            fitness += (avgTeamLeadership * -0.5) + 2;
        else
            fitness += avgTeamLeadership * 0.5;

//Technical
        //Overall Technical:
        double avgTeamTechnicalSkill = 0;
        double totalTeamTechnicalSkill = 0;
        foreach (teamMember member in teamMembers)
        {
            //this calculates the average level of
               technical skill of the team
            totalTeamTechnicalSkill =
               totalTeamTechnicalSkill + member.technical;
```

```
        }
        avgTeamTechnicalSkill = totalTeamTechnicalSkill /
           teamMembers.Count();
        fitness += avgTeamTechnicalSkill * .4;

        //CFD:
        if (teamMembers.Max(c => c.CFD) < .65)
            isFeasable = false;
        fitness += teamMembers.Max(c => c.CFD) / 10.0;
        fitness += teamMembers.Average(d => d.CFD) / 6.0;
        //CAD:
        if (teamMembers.Max(c => c.CAD) < .65)
            isFeasable = false;
        fitness += teamMembers.Max(c => c.CAD) / 10.0;
        fitness += teamMembers.Average(d => d.CAD) / 6.0;
        //FEA:
        if (teamMembers.Max(c => c.FEA) < .65)
            isFeasable = false;
        fitness += teamMembers.Max(c => c.FEA) / 10.0;
        fitness += teamMembers.Average(d => d.FEA) / 6.0;

//Motivation
        double avgTeamMotivation = 0;
        double totalTeamMotivation = 0;
        foreach (teamMember member in teamMembers)
        {
            //this calculates the average level of
               motivation of the team
            totalTeamMotivation = totalTeamMotivation +
               member.motivation;
```

```
            }
            avgTeamMotivation = totalTeamMotivation /
               teamMembers.Count();
            fitness += avgTeamMotivation * .25;


            return new Tuple<double, bool>(fitness,
               isFeasable);
        }
    }
}
```