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Collaboration Task-Technology Fit for Student Distributed Engineering Design Teams*

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Engineers in industry are increasingly called on to work with teammates located in multiple geographic locations (virtual teams). Engineering education has an interest in helping students learn how to best collaborate in these types of situations. Four years of multi-university, multi-disciplinary engineering capstone projects are investigated and related literature is thoroughly examined to demonstrate which collaboration tools, at different stages of the product development process, meet the needs of virtual team members for communication tasks. Student engineering design teams with team members located at various locations should, during the early, middle, and late stages of the product development process, emphasize the use of collaboration tools that will best meet the needs of each stage. In the early stages, teams should emphasize rich communication mediums, such as in-person kick-off meetings. In the middle stages, tools which allow team members to perform their individual work while staying in-sync with their remotely located teammates, such as web conferencing and shared data editing tools, become important. In the late stages, as the team shifts from digital work to physical work, tools such as texting and in-person meetings become more necessary.

Keywords: virtual teams; collaborative learning; computer-mediated-communication; systems engineering

1. Introduction

Before the advent of distributed design and manufacturing, collaboration in engineering design projects was a relatively straightforward effort. Given their close physical proximity, when two or more people needed to coordinate their design efforts, they sought each other out and spoke in person. Today, with increased dispersed design and manufacturing capabilities [1–3] teams that develop and manufacture those designs have to adapt and use new collaboration techniques. Such changes suggest approaches to teaching engineering design at universities should also adapt.

One area in which teaching of engineering design should adapt is in the teaching of communication tools. Aerospace Partners for the Advancement of Collaborative Engineering (AerosPACE), a program sponsored by Boeing, is one example of how industry and academia are attempting to adapt and better prepare engineering students for the changing environment [4–8]. In AerosPACE, students from various universities majoring in various technical disciplines are combined into teams with experienced professors as coaches to design, build, and fly Unmanned Aircraft Systems (UAS) that performs a specific mission. The program has grown from 19 students from four universities in 2012–2013, to 72 students from 8 different universities for the 2015–2016 academic year, for a total of more than 150 total students.

A question that is often asked in this type of situation is, "At a given stage of the project's development, what type of collaboration between team members is optimal?" [9, 10]. In this research, we have addressed this question by examining and evaluating various collaboration tools and their uses. While some papers have looked at task-technology fit in the context of general teams [11], this paper fills a niche by applying task-technology fit in the context of dispersed design and manufacturing teams, composed of engineering students at multiple locations. We call upon 4 years of AerosPACE experience, combined with current literature, to provide information on which collaboration tools should be used at the various stages of student product development.

2. Background

2.1 Virtual collaboration in engineering

While it is not hard to accept the important connection between effective collaboration and effective engineering design work [12, 13], the context in which engineering design teams collaborate has changed considerably in recent years. Virtual teamwork, where at least one team-member's interactions with the rest of the team is mediated by

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time, distance, or technology [14], has been on the rise over the last several years. 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 [15]. Other researchers agree, adding that most large companies use virtual teams in at least some way [16] 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 [17].

Engineering industries have also increasingly used virtual teams as their operations have become more global. In a 2003 study of companies in the engineering, procurement, and construction industry, over half the companies surveyed used virtual teaming [18]. Nearly every company surveyed believed use of virtual teams would increase considerably over the next five years.

In the commercial aerospace industry, Boeing's 787 offers an example. A large majority, 65 percent, of the new Dreamliner is supplied to Boeing by dozens of other companies located across the globe [2]. 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.

The importance of this virtual, geographically dispersed type of collaboration has become apparent to engineering educators who argue that teaching engineering students how to be successful in these types of situations is crucial for overall career success in modern industry [19, 20]. Lang et al. survey 15 aerospace and defense companies and note that many items important to industry are not specifically addressed in traditional engineering education and pose a question of how engineering education ought to train young engineers in virtual team collaboration [21]. Dym et al. state that "the purpose of engineering education is to graduate engineers who can design," and that design is an inherently team based, social process [9]. Given this situation in which modern engineering teams in industry find themselves, Dym and his colleagues encourage engineering educators to embrace the concept of teaching engineering courses across geographic space. The findings of these researchers are consistent with the conclusions of the American Society of Mechanical Engineering's (ASME) "Vision 2030" report which finds that industry and academia are, in some areas, fundamentally misaligned [22].

Koster et al. gave senior engineering students from four universities located around the world experience in this type of collaboration through the Hyperion project [10]. Their project attempted to use a "follow the sun" work-flow to design, build, and fly a UAS. The Follow the Sun work-flow involves three different work locations, evenly spaced around the globe such that each can work an eight-hour shift, and at the end of the shift, pass the work off to the next location. As one location leaves work to go home for the night, the sun is rising and the workday just beginning in the next. The authors commented on the fact that while communication is essential for this type of collaboration, students are generally only trained in how to communicate in local, face-to-face settings. The fact that these students were often working when their teammates were asleep, minimized opportunities to use "same time, different place" communication alternatives like phone calls [23]. These challenges were part of the project's pedagogical design as the educators wished to instruct the students through experience.

Doerry et al. created a curricular model named the Global Engineering College to help engineering students from different countries take courses together, including design courses such as robotics [19]. In their program, students from multiple disciplines, such as mechanical, electrical, and civil engineering, worked together from the Northern Arizona University campus with "outsourcing consultants" who were students studying similar disciplines in universities in Wroclaw, Poland and Dresden, Germany. Similar to the experience of Koster et al., these students found it difficult to communicate with each other and had to learn how to effectively use novel collaboration tools. This was not an easy process, and the researchers found that students did not naturally attune themselves to effective collaboration. Even when software tools custom-built for the project were presented to students, they were mostly underutilized. Students often defaulted to communicating over email. Eventually, the researchers found that media-rich, synchronous communication is important in establishing trust, commitment, and excitement among geographically dispersed team members, and that high amounts of structure may be necessary to kick-start projects of this type.

These examples show a gap in the current body of knowledge on how to effectively use collaboration tools in distributed, student design and manufacturing teams. For several years now, AerosPACE has attempted to bridge this gap by not only studying communication among teams separated by distance and disciplinary boundaries, but by also involving industry directly in preparing students for the realities of virtual engineering collaboration. By working directly with industry, we have noticed an increase in how prepared alumni of the AerosPACE program feel about entering the work force. When students were asked in a survey at the end of the 2014–2015 year of AerosPACE what skills they felt they had gained from the program, "Collaboration/Teamwork", and "Virtual Teaming" were the two most frequently mentioned items (Fig. 1). The fifth most mentioned item, behind "Manufacturing" and "Project Management (Leadership)", is "Communication". This is especially encouraging given the statement from the ASME "Vision 2030" report, that, in addition to technical knowledge, successful mechanical engineers will need to, ". . . have excellence in communication, management, global team collaboration, creativity, and problem-solving skills" [22]. This effort by AerosPACE to prepare students for work in industry is certainly being seen in the skills and attitudes of the students that go through the program.

2.2 Mediums of communication

Various methods of communication for virtual teams are available, each with its own characteristics and qualities. Maruping and Agarwal, along with Levi, emphasize that virtual collaboration effectiveness depends largely on using the correct communication medium for the task [23, 11]. It follows that knowing and understanding the characteristics of the various types of tools available for collaboration is essential to effective team communication. In the case of face-to-face conversation, multiple forms of communication, such as words, voice inflection, facial expressions, and body language (along with others) are all transmitted and received simultaneously. Most of these, however, are missing in the case of a text message.

Communication mediums have various characteristics by which they 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 [24]. An example of a rich communication medium would be face-to-face communication, while an example of a low richness communication medium is a simple text message. Maruping and Agarwal suggest five criteria for determining media richness (immediacy of feedback, symbol variety, parallelism, rehearsability, and reprocessability), while Driskell et al. give six (co-presence, visibility, audibility, cotemporality, simultaneity, and sequentiality) [14, 11]. Other researchers have similarly suggested their own sets of criteria [25–27].

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 six metrics: Media Richness, Symbol Type, Time to Response, Permanence, Parallelism, and Accessibility.

Media Richness we define in the same way as Daft and Lengel described above. Symbol type is defined 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 [9, 28]. We propose that in addition to these 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

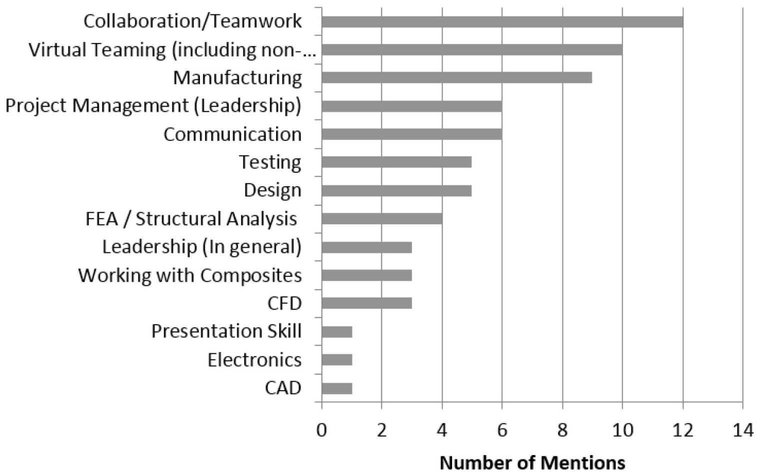

Fig. 1. Students indicated which skills they felt AerosPACE had helped them to gain.

always desirable; however, in certain situations such as group brainstorming, a less rich medium is beneficial to the communication efforts of a team ([23] see pg. 236).

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. As an example, 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 an extended period.

Permanence explains how easily the contents and sequence of an exchange are recorded and later reviewed. 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 exist, but for this definition we consider only whether tools have built-in characteristics of 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 carry on more than one conversation at a time. However, when sending text messages, it is common to be involved in multiple conversations simultaneously.

Accessibility addresses the fact that some communication tools require either special skills or special software to use them effectively. For example, to successfully use video conferencing over the internet, all participants must have the required software. They must also all have the necessary hardware, such as a webcam, and the knowledge to use the software and hardware tools. 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 face-to-face. Having to travel significant distances to communicate face-to-face affects the accessibility of this medium in today's engineering environment.

Considering each of these characteristics, a clearer comparison can be drawn among the various communication mediums available to virtual teams. We adapt the lists of communication tools from Maruping and Agarwal [11], Driskell et al. [14], Daft and Lengel [24], French et al. [25], and Levi and Rinzel [26] for our use: Face-to-face, Telephone (one to one), Teleconference (many to many), Text / Instant Messaging, Web Conferencing, Video Conferencing, Email, Shared Database, and Social Media.

Dennis et al. present various communication tools and how each is rated on a scale of low to high, slow to fast, or few to many [29]. Maruping and Agarwal also present some information on the ratings of various communication tools, while also including media richness [11]. Based on these findings, a comparison of these tools has been summarized and can be seen in Table 1.

Although most of these communication and collaboration tools are well known and easily distinguishable, some of them deserve slightly more description to avoid ambiguity. Teleconferencing, web conferencing, and video conferencing are all similar in some ways, but distinct in others. In this paper, we define teleconferencing as a telephone call for more than two people. Web conferencing includes the same services as teleconferencing and adds internet based tools that allow participants to share screens, view slides, or chat. Thus, web conferencing uses more symbol types than teleconferencing. Video conferencing tools, such as Skype, can include all the previously mentioned capabilities as well as the ability to see a live video feed of each

Table 1. List of communication tools and their ratings based on communication metrics

Communication Tool	Media Richness	Symbol Type	Response Time	Durability	Parallellism	Accessibility
Face-toFace	Highest	Multiple	Low	Low	One	Low or High
Phone Call	Medium	Audio	Low	Low	One	High
Teleconference	Medium	Audio	Low	Low	One	Medium
Text/Instant Message	Low	Text	Medium	Medium	Multiple	High
Web Conferences	Medium-High	Multiple	Low	Low	One	Medium
Video Conferences	High	Multiple	Low	Low	One	Medium
Email	Low	Multiple	Medium	High	Multiple	High
Shared Database	Medium	Multiple	Medium	High	Multiple	Medium
Social Media	Low-Medium	Multiple	Medium to High	High	Multiple	Medium

participant. Previously, video conferencing involved purchasing expensive equipment and software, but has now evolved to being available through web based applications and using relatively inexpensive equipment.

3. Methods

This study includes 150 students from four academic years, consisting of 128 males and 22 females enrolled in several different universities and colleges across the United States. Participating institutions were Brigham Young University, Georgia Tech University, Purdue University, Tuskegee University, Embry Riddle Aeronautical University, Clemson University, Washington State University—Pullman, Washington State University—Everett, and Everett Community College. The average age was 22.9 years old (SD = 2.49) and included mechanical engineering, aerospace engineering, manufacturing engineering, electrical engineering, and computer engineering majors. The project lasted for two semesters (late August through April) and teams worked together for the duration of the project. Surveys were administered four times throughout the project at the midpoint and end of each semester (approximately 6, 14, 23, and 30 weeks). Institutional Review Board (IRB) procedure were followed where students were assured that responses were kept anonymous, wouldn't be shared with other students, and wouldn't affect students' grades. This was done to ensure honest and accurate results [30]. Responses from surveys were used to gather information about the communication patterns and experiences of students. An example of the survey administered may be found in Appendix I.

4. Proposed model of collaboration

Dieter and Schmidt have proposed a product development process that includes three stages for a product design process: Conceptual Design (which includes getting customer requirements, defining the objectives, and generating concepts), Embodiment Design (which includes determining overall product architecture and individual design of parts), and Detailed Design (which includes the detailed design of all parts, part integration, and creation of final schematics) [31]. NASA has also developed a toolbox with their own suggested workflow [32]: Conceptual Trade Studies, Concept Definition, Design and Development, Fabrication, Integration, Test, and Evaluation, and Operations.

These two processes are similar in stepping through concept generation and design, with NASA adding in the manufacturing, evaluation and utilization sections of the product life-cycle. We combine the NASA model with Dieter and Schmidt's process, and simplify them to create three basic phases: Early, Middle, and Late. As a general overview, the early stage encapsulates the conceptual trade studies and concept definition. The middle stage incorporates the detailed design and development of the product. The late stage includes the fabrication, integration, test, and evaluation of the product. In the following sections, each stage will be explained in greater detail.

We will provide, based on our own experience and literature, a suitable model for which collaboration tools should be used during each of the three mentioned stages. This model is intended as a guide for distributed student design and manufacturing teams. The synthesized information will allow for students and professors to better understand which collaboration tools should be used during a product design team's life-cycle.

4.1 Early stages

The early stage of the design process in AerosPACE is defined by teams creating a mission definition (based on customer requirements), generating multiple concepts, and evaluating the concepts until one has been selected for detailed design. The main goal for communication during this stage is to create a cohesive relationship between team members that will enable successful dialogue in the future and to convey created concepts and evaluations to team members.

While there are specific communication tools that help encourage a good working relationship, we have learned in our experience with AerosPACE that whenever possible, in-person meetings, such as a program kickoff, should be held. In the 2013–2014 AerosPACE year, no in-person kickoff meeting was held, but students did meet each other in person at the end of the academic year. Afterwards and during course evaluations, students indicated that many of the issues or problems they faced throughout the year, such as personality conflicts, could have potentially been minimized or eliminated if they had met in person at the beginning of the year. For example, one student, when asked whether he felt a kickoff meeting would have helped with some of the interpersonal challenges 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."

At the beginning of the following year (2014–2015), a kick-off meeting was held, at which all students from all teams met in one location. They brainstormed, conducted team-building activities, began work on responding to the program Request for Proposals (RFP), and socialized during dinner. Later, when asked what portions of AerosPACE they felt had gone well, the second most mentioned item was the kickoff meeting. 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."

Other researchers agree [33]. Siebdrat et al. stress the importance of a kick-off meeting to help virtual teams develop a shared understanding of the project and encourage social cohesion [34]. This shared understanding of the roles, skills, and responsibilities of each team member along with a general knowledge of the project is often referred to as a shared mental model and is critical in the formation and overall success of a team [35]. Lovelace et al. state that one reason dispersed teams struggle with forming a shared mental model is 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 [36]. Hackman also agrees that even well-structured virtual teams need to have everyone physically present for a launch meeting [37]. In some instances, a kick-off meeting might not be practical, such as in the case of a short project life-cycle or for a team that has already had extensive experience working together. In these instances, a kick-off meeting may still be beneficial for establishing team roles and deciding upon a mission definition, but perhaps not as critical as a newly formed team.

After an in-person meeting has been held, it's important to use communication tools that are high in media richness, allowing for the growth of the relationship among team members [38]. Tools such as video conferencing become valuable due to high media richness [11] and can enable participants to develop trust and cohesion through a richer interaction [23]. This is especially critical as teams define the mission specifications, since this is when team members begin forming the norms that are critical to effective communication and making one of their first critical decisions. Teleconferencing and web conferencing are also viable options, but should defer to video conferencing when possible, as their level of media richness is lower.

Video conferencing is beneficial during this stage due to the low level of parallelism and low time to respond. As stated by Malhotra et al., virtual meetings are most successful when team members are engaged in the meeting and not distracted [39]. Communication tools with higher levels of parallelism allows team members to multi-task while in a meeting, causing dissonance or a lack of participation [40]. A slightly higher order skill that we have also found useful, is for meeting leaders to request verbal confirmation from specific participants to confirm reception of messages and engagement [23, 39]. As Dennis and Valacich suggest, feedback (or time to response) becomes important when the goal of communication is to achieve convergence [41]. By using video conferencing, with its low time to response, student teams that have never worked together previously can build a cohesive relationship and better come to a consensus about the mission requirements.

There are times when video conferencing or web conferencing may not be a viable option due to accessibility. Although these tools offer the highest levels of media richness, they are also prone to technical difficulties. Levi et al. emphasize the need to learn how to use these tools effectively to reduce such difficulties and misunderstandings [23]. In AerosPACE, we have experienced first-hand the saying, "Technology always adds to a meeting, and it's usually about 15–20 minutes". Thus, ample time should be given for instructing team members on the correct way to use each communication tool and allowances given to team members when software doesn't behave as expected. 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. Test-runs should be performed with the chosen communication tool to help reduce these difficulties. A slightly higher order skill that we have found useful in video conference meetings is for leaders to request verbal confirmation from specific participants to confirm reception of messages during meetings [42].

After the mission definition has been selected and design teams begin to form numerous preliminary designs, the focus should move to communication tools with high symbol variety and low permanency. This transition will help to facilitate an exchange of technical data required during the conceptual design and reduce the amount of relational conflict [43]. For design teams, research has shown that teams which sketch and generate more ideas during the conceptual stages are more likely to be successful [44–46]. Web conferencing then becomes a useful communication tool, as it allows for sketches and concepts quickly drawn on a computer to be shared with team members

4.1.1 Recommended tools for early stages

In summary, for the early stages of a virtual team, we recommend that extra consideration be given to tools with high media richness, multiple symbol types, low time to response and low parallelism. To achieve these communication types, we recommend the following communication tools: Face-to-Face meetings, Video Conferencing, and Web Conferencing. These communication tools should be taught and employed by virtual design teams to develop a good working relationship, form a shared mental model of the task and team skills, and generate the most ideas possible.

4.2 Middle stages

As team members understand the task that needs to be accomplished, they narrow the design and select a specific concept. The middle stages begin after the concept has been narrowed to one specific design, and span product architecture development, configuration design, and detailed design. Work begins in earnest with specific integrated product teams (IPTs) prototyping sub-systems and incorporating them into the overall detailed design [31]. Detailed design brings individual portions together, most system-level decisions are finalized, and a decision is made by team management to release the design for production [31]. Communication goals for this stage are to effectively communicate design schematics and details, coordinate component interfaces among multiple IPTs, and document design decisions.

Assuming that sufficient levels of trust among team members were established during the early stages of the project, some forms of communication are less necessary during the middle stages. 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 not as necessary and less expensive or more convenient mediums can be used more effectively in this stage [19, 47]. Thus, tools with less media richness should be exchanged for communication mediums that provide high permanency, high time to respond, and multiple symbol types.

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 easy review. The importance of being able to easily capture design rational has been highlighted by researchers such as Bracewell et al. [48] and Klein [49]. Hepworth et al. found that virtual teams that use a documented 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 [50].

For these reasons, all team members should be made familiar with tools that allow a shared database like Google Drive, MS Sharepoint, or other similar cloud storage systems. Hackman states that an information system is critical to the group's ability to plan and execute a performance strategy [51]. The permanency of a shared database allows team members to document design decisions, reference other team members' work, and stay up to date on the progress of others.

In AerosPACE, we have explored different options for such an online collaborative platform. During the 2013–2014 and 2014–2015 program years, students mentioned their dissatisfaction with the chosen tool, in large part because of the poor file organization capabilities. 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, access to Google Drive was restricted for team coaches from Boeing. To remedy this situation, MS Sharepoint, which can be federated via security protocols, was implemented in the 2015–2016 program year allowing teams to create and share items such as Gantt charts and task lists as well as organizing files and folders. An example of one team's use of the system can be seen in Fig. 2. This screenshot shows how any team member can, in one central location, access schedule information, find files, and view the latest information posted by teammates and faculty on the Newsfeed. In the upper half of the screenshot is a Gantt chart showing the schedule for all members of the team. The lower left shows where the files are stored and organized, with recent posts in a forum-like format in the lower right side. Other apps can be added or removed as the team chooses. In addition to MS Sharepoint, edX was also used as an online organizer for all classroom material (e.g., lecture recordings, slides, handouts). Although edX allowed for seemingly better organization and easier access, students neglected edX, preferring instead one all-encompassing tool that would house their classroom needs. This highlighted the fact that ease of access was critical in selecting an online collaborative platform.

Time to response also becomes an important factor during this stage. In the middle stages, the work a design team performs is often technically complex. Scheduling challenges imposed by working across time zones and varied individual schedules, also adds to the difficulty of communicating simultaneously. For these reasons, AerosPACE students indicated in the survey that they preferred tools that allowed for a longer time to response, such as texting, email, or shared databases for the transfer of information. These types of tools allow students to receive a message, think about the implications of that message, and then respond appropriately when most convenient. In one instance, a student received a question from a faculty coach, thought about what the question

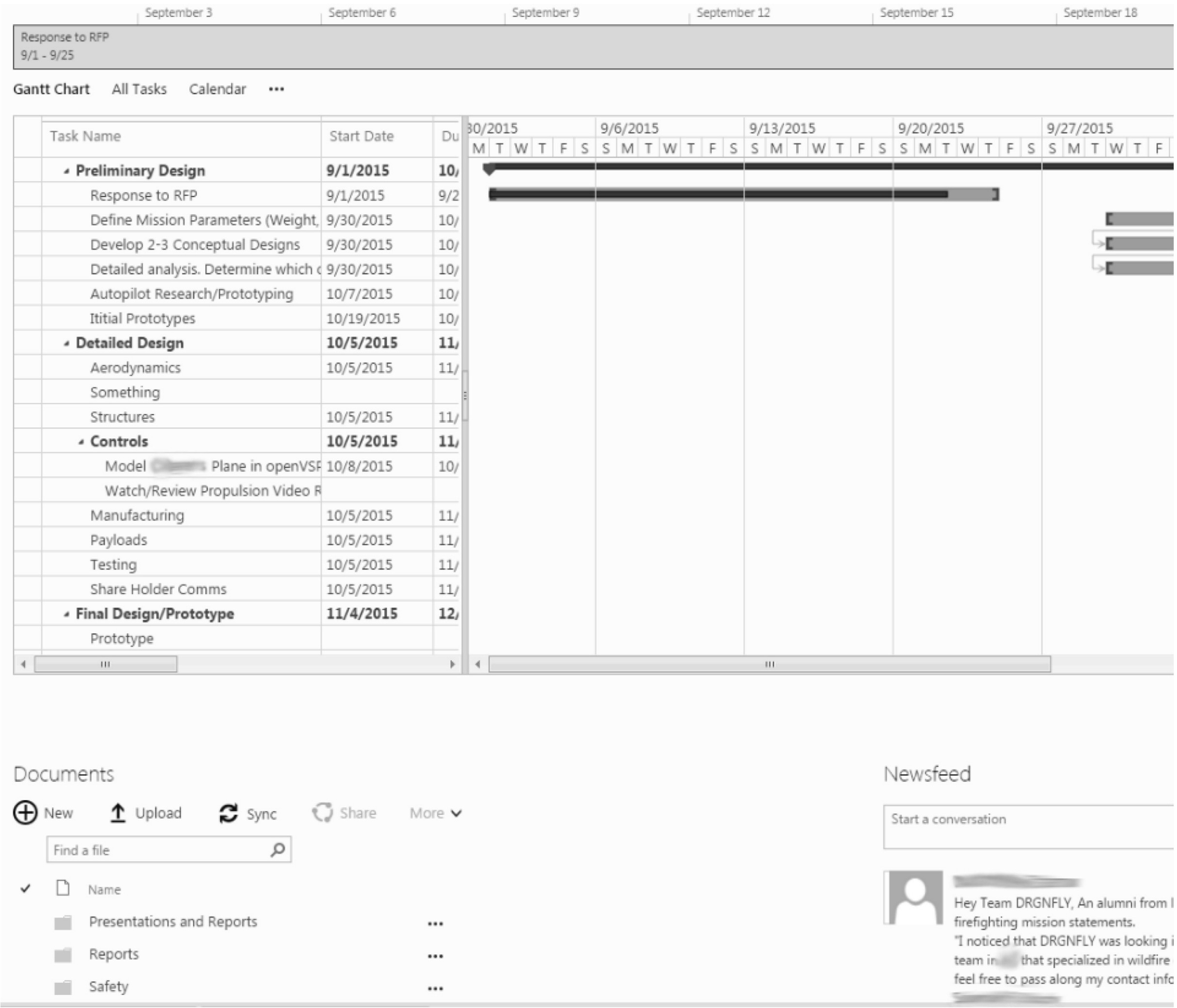

Fig. 2. Screenshot of a team page showing a Gantt chart, file-folder organization system, and team discussion thread.

entailed, took the time necessary to perform the required calculations, and answered the question. The use of having a high time to response is also backed up by Maruping and Agarwal, who propose that teams that use communication tools with a high time to response for managing process conflict will be more effective than teams that use communication tools with other functionalities [11].

Technologies that allow for multiple symbol types are important during this stage of the project. Databases, as mentioned before, and email are useful for design teams as they allow for almost any symbol type to be transmitted. While these technologies are typically low in media richness, they focus on the substance of group tasks. These features allow for multiple team members to simultaneously participate in the task discussion and decision making process and generally gives an improved decision quality [52, 53]. By thus using email or shared databases, design teams will be better equipped to share the specifics of their designs, make high quality decisions, and document design decisions.

4.2.1 Recommended tools for middle stages

In summary, for the middle stages of a virtual team, we recommend using tools that are high in permanence, high in symbol variety, and high in time to respond. As such, the following communication tools are recommended: Web Conferencing, Shared Database, and Email. These tools will help a team to document design decisions, collaborate between IPTs about sub-system interfaces, and effectively share the technical data generated from their design work.

4.3 Late stages

The late stages include early full prototyping, testing, and final manufacturing. This portion of the project is characterized by a distinct shift from digital to physical work. Small changes are sometimes made to the design, but for the most part the team is now focused on manufacturing and full-scale testing. Physical parts are shipped to and from different locations for assembly and testing, concluding with a final assembly and showcase of the finished product. Communication tasks during this stage are reviewing design decisions, communicating fulfillment of part production, and any coordination of design changes and shipment of parts.

During the late stages, communication tools that provide medium or high permanence and low time to response allow team members to recall exact values and specifications of the design. For most teams in AerosPACE, databases were used to reference manufacturing plans, design specifications, and test results. The high permanence of databases makes them ideal for this stage, as team members may feel confident that specifications and results are consistent across all IPTs. To notify other teammates of design changes, email was generally used. These results generally agree with the findings of other researchers, such as Maruping and Agarwal, who hypothesize that virtual design teams during the later stages of development should use communication mediums that are low in time to response and high in permanence [11].

Although analysis and testing are relatively easy to document in a database for remotely located teammates to view, physical work is not. To overcome this challenge, AerosPACE teams have developed interesting techniques. For example, students in one team would use their phones to take photographs of their work and post them on social media with a short caption, such as ‘‘Brand spankin' new carbon fiber ribs!'' as shown in Fig. 3. The accessibility and permanence of social media allow remote teammates to observe their work, identify potential errors, and offer suggestions, with minimal effort in recording. The entire team is thus aware of the team's progress and can adjust their plan accordingly.

Communication tools that are high in parallelism and accessibility are necessary to coordinate the efforts among multiple manufacturing groups in a timely manner. Easily accessible communication, such as texting, allows double-checking of numbers and dimensions before the final manufacturing and shipment of parts [54]. The accessibility of texting is high 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. Fig. 4 shows two examples from AerosPACE of messages exchanged 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 one

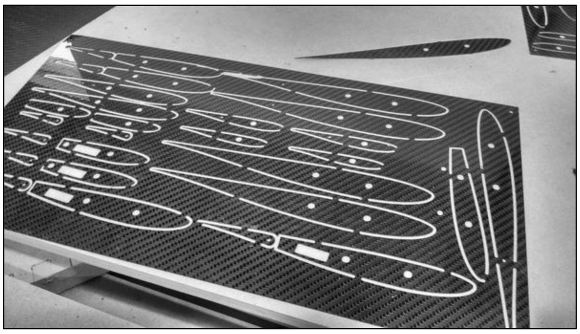

Fig. 3. Photo of carbon fiber ribs sent over social media to show progress of manufacturing.

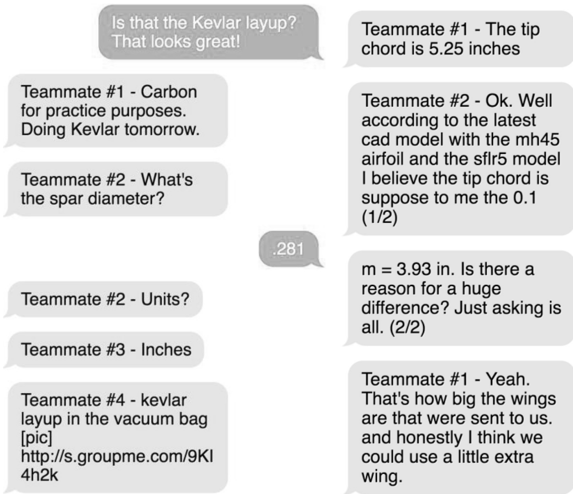

Fig. 4. Examples of group text messages among teammates during the late stages of the product development process.

teammate commending the efforts of another, and then later verifying a critical dimension. Both are good examples of how texting allows for more efficient coordination due to the high accessibility and parallelism of the tool.

Finally, our experience has shown that in the final stages of the project, it is highly effective to allow at least some teammates from different locations to work on-site with their teammates. This idea is supported by researchers such as Hinds and Bailey, and Grinter et al. [55, 56]. For example, after one unsuccessful flight attempt which ended in a crash, one team with students from multiple universities used GroupMe to see who would be willing to help fix the UAS. Since most of the team was on-site, they were able to regroup and rebuild the plane within 24 hours of the crash. This feat was accomplished in part by the colocation of the team and the use of texting.

4.3.1 Recommended tools for late stages

In summary, for the late stages of a virtual team, we recommend that extra consideration be giving to

Table 2. Suggested communication tools for each stage of the design process

Communication Tool	Early Stages	Middle Stages	Late Stages
Face-to-Face	X		X
Phone Call			
Teleconference		X	
Text/Instant Message			X
Web Conference	X	X	
Video Conference	X		
Email		X	X
Shared Database		X	X
Social Media			X

communication tools that are low in time to response, high in permanence, high in parallelism, and high in accessibility. As such, we recommend using the following communication tools: Shared Database, Email, Text Messaging, and Face-to-Face Meetings. These communication tools are essential for allowing a team to quickly access and verify design parameters during manufacturing and integration of parts in the completed model. Face-to-face meetings allow for teams to quickly fix or modify any parts that don't adequately fulfill the need of the team.

5. Discussion

We have found that each stage of the product development process has unique needs that should be responded to with specific tools. Table 2 shows a summary of which tools we recommend should be given extra consideration during each stage. For the early stages of a virtual team, we recommend that extra consideration be given to tools with high media richness, multiple symbol types, low time to response and low parallelism. For the middle stages, we recommend using tools that are high in permanence, high in symbol variety, and high in time to respond. For the late stages, we recommend that extra consideration be giving to communication tools that are low in time to response, high in permanence, high in parallelism, and high in accessibility. Following these steps will ensure the strengths of the tools being used best match the communication needs of the team during the various stages of design and manufacturing.

Universities wishing to evolve their capstone courses by engaging with other institutions in multi-site, multi-disciplinary, virtual teaming model should consider this research. We recommend students and faculty be trained regarding how virtual engineering teams can increase their communication effectiveness by matching the communication tools with the stage of the design process. Be practicing how to most effectively use such tools, the experience for both students and faculty can be much more meaningful and positive.

Virtual design teams 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 [28]. We believe that helping students to understand the concepts presented in this research, becoming cognizant of the strengths and weaknesses of their choice of communication tool, can help them to address and overcome many challenges of such capstone courses.

6. Conclusions

This research identifies, through a review of the literature and the experience of the authors with several years of multi-university, multi-disciplinary capstone projects, which remote collaboration tools should be used at different stages of product development and production. We evaluate collaboration tools based on the criteria of richness, symbol type, time to response, permanence, parallelism and accessibility. Tools were evaluated on a product development process defined as early, middle, and late stages.

During the early stage, 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 and video conferencing should be used to develop the team relationship and generate ideas.

During the middle stage, the team should transition to web conferencing, email, and shared databases to help give permanence to design decisions and allow team members time to formulate an adequate response to detailed questions about technical data. During the late stage, the team should rely on the databases used in the middle stages, email, and text messaging to verify design values and give updates on manufacturing progress. Where possible, teams should meet face-to-face at the end of the late stage to integrate the sub-systems into the final product and troubleshoot any problems.

This research shows that at different stages of a project, specific tools should be given extra consideration by student engineering design teams that are geographically or otherwise separated. Tools that better meet the needs of teams at a given stage will enhance communication effectiveness, and teaching students when to use which communication tools will better prepare students to work in an increasingly virtual world.

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Appendix I

Team and Peer Evaluation Survey

Unless otherwise noted students were given a choice of 5 responses. Option A corresponds to Very Dissatisfied, Dissatisfied, Neutral, Satisfied, Very Satisfied. Option B corresponds to Very Poor, Poor, Fair, Good, Very Good. Option C corresponds to Very Low, Low, Neutral, High, Very High. Option C corresponds to Strongly Disagree, Disagree, Neither Agree or Disagree, Agree, Strongly Agree.

Q3 Think of the team that you are part of. How satisfied are you with your team? (A)

Q4 How would you rate your team's overall communication? (B)

Q5 How would you rate your team's overall level of trust between its members? (B)

Q6 How would you rate your team's overall level of technical competency? (B)

Q7 How would you rate your team's overall level of commitment to achieving the project goals? (C)

Q8 In what area do you feel is your team's greatest strength (currently)?

Motivation/Interest in the Project (1), Technical Skill (2), Social Skill (3), Leadership (4), Other (please explain): (5).

Q9 In what area do you feel is your team's greatest weakness (currently)?

Motivation/Interest in the Project (1), Technical Skill (2), Social Skill (3), Leadership (4), Other (please explain): (5)Q10 What examples or other explanations can you offer regarding your answers to the two previous questions?

Q11 About how often do you work with each of your peers? (Mark yourself as "All the Time")

	Not At All (0)	Rarely (1)	Occasionally (such as once a week) (2)	Often (twice a week or more) (3)	All the Time (nearly every time you work on the project) (4)
Teammate (1)	○	○	○	○	○
Teammate (2)	○	○	○	○	○

Teammate (3)	○	○	○	○	○
Teammate (4)	○	○	○	○	○
Teammate (5)	○	○	○	○	○

Q13 Please rate each of your peers in the following areas:
(Please rate yourself as well)

Q14 Teammate (1)

	Very Poor (1)	Poor (2)	Fair (3)	Good (4)	Very Good (5)
Motivation/ Commitment to the Project (1)	○	○	○	○	○
Technical Skill (2)	○	○	○	○	○
Social Skill (3)	○	○	○	○	○
Leadership (4)	○	○	○	○	○

Q25 If you would like to recommend one of your team members, please select his/her name. If not, please select, "No, thanks."

Q26 Please select the area(s) you would like to recommend him/her in:
Motivation/Commitment (1), Technical Skill (2), Social Skill (3), Leadership (4), Q27 Please describe why you want to offer your recommendation for this person's Motivation/Commitment:

Q28 Please describe why you want to offer your recommendation for this person's Technical Skill:

Q29 Please describe why you want to offer your recommendation for this person's Social Skill:

Q30 Please describe why you want to offer your recommendation for this person's Leadership:

Q31 How much do you work with your team's Coaches?

	Not at All (0)	Occasionally (1 or 2x/month) (1)	Often (approx. 1x/ week) (2)	All the Time (3)
Coach (x)	○	○	○	○

Q32 Rate your agreement with the following statement:
"The Coaches had the skills and knowledge necessary to help my team be successful." (C)

Q33 Rate your agreement with the following statement:
"Overall, the Coaches were an asset to my team." (C)

Q34 What suggestions can you offer for how support from the coaches can be improved?

Q37 Would you recommend the AerosPACE program to a friend? (Yes or No)

Q38 Knowing what you know now, if you could go back, would you again choose to participate in the AerosPACE program? (Yes or No)

Q39 What skills did you learn as part of AerosPACE that you think will apply to your career (whether in academia or industry)?

Q40 Thinking of the AerosPACE program in general, what things do you feel went well?

Q41 Thinking of the AerosPACE program in general, what things do you feel need improvement?

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