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# SOME (TEAM) ASSEMBLY REQUIRED: AN ANALYSIS OF COLLABORATIVE COMPUTER-AIDED DESIGN ASSEMBLY

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## ABSTRACT

*Previous efforts in the area of collaborative computer-aided design (CAD) suggest that a team of designers working synchronously in a multi-user CAD (MUCAD) environment can produce CAD models faster than a single user. Our research is the among the first to investigate assemblies in MUCAD. Due to the lack of hierarchical feature dependency in assemblies, we propose that CAD teams can optimize assembly through modularization and parallel execution. In our study, 20 participants were tasked with assembling pre-modelled CAD parts of varying complexity in teams of one, two, three or four. We analyze audio recordings, team activity, and survey responses to compare the performance of individuals and virtual collaborative teams during assembly, while working with the same MUCAD platform.*

*This paper features a multimodal approach to analyze team trends in communication, workflow, task allocation and challenges to determine which factors are conducive to the success of a multi-user CAD team and which are detrimental. In our work, the success of a team is measured by its productivity score, which is the number of mates added by a team within a given time frame. We present evidence that teams can complete an assembly in less calendar time than a single user, but single users are more efficient based on person-hours, due to communications and coordination overheads. Surprisingly, paired contributors exhibit an assembly bonus effect. These findings represent a preliminary understanding of collaborative CAD assembly work. Our work supports the claim that collaborative assembly activities have the potential to improve the capabilities of modern product design teams, delivering products faster and at lower cost. We identify areas for future research, and highlight areas of improvement for collaborative CAD platforms and engineering design teams.*

## 1. INTRODUCTION

Computer-aided design (CAD) software has traditionally been a single-user tool that either limits or prohibits collaboration within design teams. In practice, however, the development process of any product, both simple and complex, involves the contribution of several engineers and colleagues [1]. For geographically-dispersed teams, designers working across different companies, or design teams that wish to collaborate to solve early design conflicts, the solution is often to download and email the CAD file, or upload files to PDM (Product Data Management) services [2]. In recent years, companies like Onshape and Autodesk recognize the need for a more robust method to collaborate in CAD. Collaborative CAD enables a group of designers to edit and review their design interactively, concurrently and synchronously [3]. Existing research of collaborative CAD has focused on: part modelling [4]; identifying the benefits of collaborative CAD [5]; and comparing single-user CAD to multi-user CAD (MUCAD) modelling [6].

To date, minimal research has investigated the assembly phase of CAD design work in a collaborative CAD environment, despite the significant impacts that successful assembly planning can have on a product's development [7]. In a typical product life cycle, 20% of the final cost and 50% of production time is from assembly [8]. Therefore, it is crucial to gain a deeper understanding of how CAD assemblies are made, using the modern tools that are available to designers today. We propose that collaborative CAD has the potential to change the way design teams optimize the assembly process.

We present the results of an experiment which studied how groups of one to four collaborate during synchronous CAD assembly to find best practices in team assembly work. The findings from this research may help CAD designers decide how many people should contribute to the same CAD assembly, how to maximize productivity, and how to distinguish high performing CAD teams from low performing CAD teams. Our work also considers qualitative participant feedback to provide valuable insights for the advancement of collaborative CAD platforms.

### 1.1 Research Questions

This paper seeks to answer the following four questions:

1. To what extent do multi-user teams demonstrate increased productivity versus one person working in the same collaborative CAD platform?
2. How does the complexity of the assembly affect the way in which teams and individuals complete an assembly task?
3. How do the best performing teams communicate compared with the worst performing teams?
4. What are common challenges in collaborative CAD assembly? How can CAD systems be improved to assist collaborative assembly?

## 2. BACKGROUND

### 2.1 CAD Assembly

"Assembly" broadly refers to "the addition or joining of parts to form the completed product" [9]. In the context of CAD, an assembly is a model composed of components and/or subassemblies connected by mates and assembly relationships [10, 11]. This differs from part modelling, which is the modelling of product elements that are manufactured in one single piece [11]. The aforementioned relationships consist of constraints, mates or links that describe the relative position of each component in an assembly [11]. Mates can define the position and motion of components in relation to each other. For example, a mating condition can be added to align holes concentrically, or to make two faces parallel. In addition to mating conditions, components can also be positioned within the assembly by way of absolute coordinate placement methods. The final position of each component based on these relationships is calculated using a geometry constraint engine built into the CAD system.

Mating conditions can vary depending on the CAD system being used. In the collaborative CAD system, Onshape, the movement (degrees of freedom) between two instances is embedded within the mate, thus only one mate can be added between any two entities. When modelling a simple fan assembly, the traditional CAD package, SolidWorks, requires two mates between the pin and fan: (i) a coincident mate to limit translation in the Z direction and (ii) a concentric mate to align the two parts (Fig. 1). In Onshape, only one revolute mate is required, which constrains all motion except for rotational movement about the Z axis.

Past research regarding CAD assembly has focused on understanding and optimizing assembly sequence planning (ASP), evaluating assembly similarities, assembly model retrieval, and automating the assembly process [12–18]. Yet no work exists to explore how to optimize CAD assembly when using collaborative CAD.

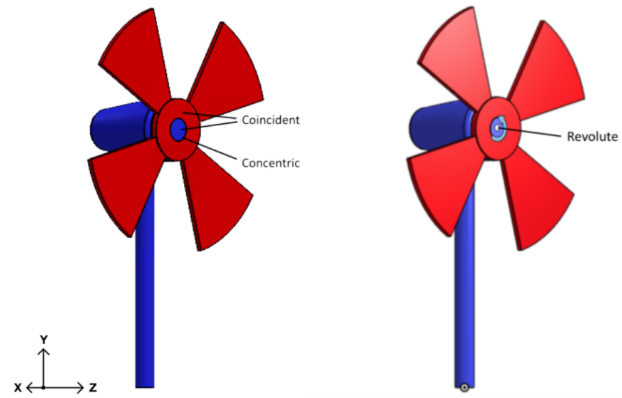


**FIGURE 1**. FAN ASSEMBLY MATES IN SOLIDWORKS (LEFT) AND ONSHAPE (RIGHT)

### 2.2 Assembly Complexity

Researchers in various fields have extensively explored the concept of complexity, resulting in a wide range of definitions and methods to measure complexity [19]. In general, a "complex assembly" describes a difficult and demanding assembly. Though, existing complexity models are theoretical and there is no universally-accepted method for measuring complexity [20]. As a result, many researchers have attempted to define complexity in the context of assembly. Rodriguez –Toro et al. suggest that complexity can consist of two main types: component and assembly complexity, where component complexity is related to the geometry of components and assembly complexity is related to the product's architecture and the number of operations (mating relationships) required to create an assembly [21]. Alkan et al. defines the complexity of a product as the degree in which both the complexity of the assembly components and their mating relationships cause difficulties during the handling or fitting processes in assembly [22]. Evidently, there are many different, yet valid, definitions and understandings of assembly complexity.

Falck et al. interviewed 64 engineers involved in design and manufacturing to study how industry professionals understand the concept of assembly complexity [23]. The engineers responded that a complex assembly can have the following characteristics: (1) many different ways of doing the task, (2) ambiguity in the positioning of parts/components, (3) lack of clear assembly order, and (4) many individual details or parts to keep track of [23]. Falck et al. also found that 92% of respondents believe there is a direct relationship between assembly complexity and assembly time [23]. This suggests that complex assemblies take longer to complete than simple assemblies.

In our research, we observe teams collaborating synchronously to assemble models of low, medium and high complexity. We investigate if and how complexity affects the assembly's completion time. We are also interested in other ways complexity can affect the dynamics of a multi-user CAD team. Does assembly in collaborative CAD scale well with complexity? Do teams approach a complex assembly differently than with a simple assembly? Is there a preferred complexity level in collaborative CAD?

### 2.3 Modular Assembly

The concept of modularity (or modularization) can improve the way in which assemblies are made [24, 25]. Modularity is an organizational tactic in which complex systems can be decomposed into simpler subsystems (or modules), to be managed independently [26]. For example, a modular assembly can be divided into smaller, more manageable "subassemblies", where each subassembly contains a set of components that are highly dependent on each other, but minimally dependent on components outside of their subassembly [27]. Previous work regarding modularity uses network structures to represent systems and subsystems, as a visual method to convey the connectivity or dependencies between modules [28–30].

To understand the dependencies between components and/or subassemblies, we apply a concept frequently used in software development. Feature dependency is a terminology used to describe code containing program elements that depend on other elements to function [31]. A similar idea can be applied to CAD modelling, where certain features of CAD parts depend on the existence of other features (i.e. a sketch needs to be extruded before a fillet can be added). Features in CAD modelling follow a "parent/child" relationship structure, such that each feature is connected hierarchically [32]. Due to this dependency, modifications to a parent feature will propagate to related child features [33]. Hartman explains that designers must initially strategize a modelling plan to increase efficiency and minimize errors, as improper feature sequencing can lead to longer modelling times, impossible geometries, and feelings of confusion [34]. Hence, a multi-user CAD team modelling a single part simultaneously must have heightened awareness of each other's work and also of how one member's modifications to parent features will propagate to affect another member's child features.

In CAD assembly, however, mating relationships (assembly features) do not follow a hierarchical structure. Therefore, assembly features can be added in parallel with other contributors and team members do not have to wait on each other to finish. We define this type of work arrangement as parallel execution. In computing, parallel execution is when numerous calculations or processes are executed simultaneously, and results are combined at the end, when the program is finished running [35]. We apply this concept to CAD assemblies where subassemblies can be completed in parallel with other subassemblies, resulting in a finished CAD model. To understand how a team of designers would tackle such an assembly task, we use fully-synchronous collaborative CAD software, which has never before been used to study collaborative assemblies. We hypothesize that successful multi-user CAD teams will modularize assemblies and display parallel execution.

### 2.4 Collaborative CAD

Since the formation of CAD in 1963, CAD systems have primarily focused on the interactive process between computer and a single user [6]. However, recent developments in cloud technology have allowed the CAD industry to create fully-synchronous collaborative CAD software [36]. This technology is comparable to "Google Docs," as collaborative CAD enables multiple users to simultaneously create, manipulate and contribute to the same CAD file, as well as save changes in real time [37]. Collaborative CAD has many benefits when compared to traditional single-user CAD: enhanced team communication; improved feasibility for collaboration in geographically-dispersed teams; increased parallelism between, awareness of, and care for other team members; and increased learning opportunities [38–43].

Researchers have previously studied the effects that collaborative CAD has on the design process. Eves et al. conducted a study to assess the modelling capabilities of four multi-user teams and four single-user teams when tasked with modelling a hand drill. They concluded that collaborative CAD increases communication between team members as well as heightens awareness of other team members' work [44]. Hepworth et al. showed that having multiple users contributing to a CAD file greatly reduces the amount of modelling time required [45]. However, they also found that at a certain point, having multiple users actually increases the amount of time spent modelling [45]. This trade-off suggests that there is an optimal number of simultaneous contributors in collaborative CAD, and more contributors does not always lead to better outcomes. Stone et al. investigated methods to determine the optimal team size for designers modelling a single part simultaneously. In this study, teams of 1-4 designers worked simultaneously to model parts of varying complexity. Complexity in this context is measured by the number of features required to create the part. They found that on average, the time required to model a single part decreases as the number of contributors increases, with no significant changes to the reduction of modelling time at around four contributors [4].

While there has been considerable research in collaborative CAD part modelling, no studies have investigated assembly modelling in a collaborative CAD environment. Due to parallel execution, modularity and feature dependency, we expect that these factors will play a key role in the way that multi-user teams work and allocate tasks, differing from results of previous studies that focus entirely on part modelling.

## 3. METHODOLOGY

### 3.1 Experiment Overview

The aim of this study is to analyze and compare the performance of individuals and collaborative teams during CAD assembly, using the same collaborative CAD software. As such, we hosted a synchronous CAD experiment whereby 20 participants were tasked with assembling models of varying complexity in teams of one, two, three or four members. We assigned teams such that there were two teams for each team size, totalling eight teams (i.e. two single users, two pairs, two teams of three, and two teams of four). Participants were compensated $15 per hour, for a total of two hours. Data was collected in three stages: (1) initial survey to recruit and screen participants, (2) synchronous experiment with CAD assembly tasks, and (3) post-experiment survey.

The synchronous CAD experiment can be broken down into four sections: (1) guided tutorial, (2) baseline assembly task, (3) Round 1 collaborative assembly tasks, and (4) Round 2 collaborative assembly tasks. Figure 2 summarizes the aforementioned sections.

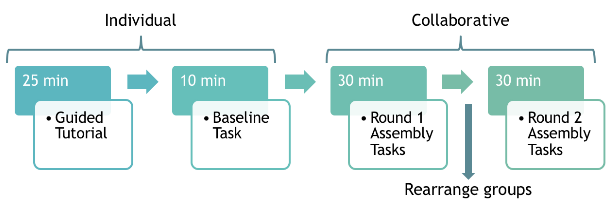


**FIGURE 2**. STAGES OF SYNCHRONOUS CAD EXPERIMENT

Due to the limitations of in-person experiments from COVID-19, the synchronous experiment was held through the online conferencing software, Zoom. To begin the study session, we required our 20 participants to join a Zoom call under a prearranged, unique alias (i.e. Participant 1, Participant 2, etc.) and with their camera switched off. Once all participants were present, we ran a 25 minute guided training session of the CAD software, Onshape, to demonstrate the user interface, collaboration features, and how to create mates. Following the demonstration, participants were given an individual baseline task of assembling a basic model in order to become familiarized with the format of the study and for the researchers to calibrate for varying skill levels.

After each participant completed the baseline task, the 20 participants were divided into eight randomly-assigned teams of one to four members to begin the Round 1 collaborative assembly tasks. Each of the eight teams was moved into a separate Zoom breakout room and was allowed to communicate via Zoom audio, messaging and screen-share only - no video. Participants could also interact through the CAD platform, using the built-in comment feature and "Follow Mode", which allows users to view another collaborator's screen in real time. Once the teams had joined their breakout rooms, the teams were given 30 minutes to assemble three different models of varying complexity. The researchers recorded each team's Zoom breakout room session for audio communication data.

After the 30 minutes had elapsed, the participants rejoined the main Zoom session and were randomly-reassigned to teams of one to four members (again with two teams for each team size, totalling eight teams), to begin the Round 2 collaborative assembly tasks. The newly-configured teams were then similarly moved into separate Zoom breakout rooms and given 30 minutes to assemble another set of three different models of varying complexity.

Immediately following the Round 2 collaborative assembly tasks, participants were free to leave the Zoom session. However to receive full compensation, participants were required to complete a post-experiment Google Forms survey to gather qualitative data and feedback. This data was used to analyze the successes and challenges from each team.

### 3.2 CAD Assembly Tasks

Each round, teams were tasked with adding appropriate mates to pre-modelled CAD parts and were given 30 minutes to complete as much of the assemblies as possible. Thus, the terminating condition for the assembly task is the time limit. Team members were allowed to allocate tasks in the manner of their choosing under the condition that they begin with the least complex model and finish with the most complex model. This being said, only two out of eight teams were able to complete all assemblies in Round 1 and no teams were able to complete all assemblies in Round 2. Each set of assemblies consisted of a low, medium and high complexity model. In this study, complexity is measured by the number of parts in an assembly and the average number of mates per part. Table 1 summarizes the complexity criteria.

For all assembly tasks (including the baseline task), participants were provided the pre-modelled part files and a task guide containing snapshots of the fully-assembled model from multiple views, as well as a short video of each assembly in motion, when properly assembled. The purpose behind providing pre-modelled parts is to ensure that the parts are consistent across all teams, such that CAD teams are only evaluated on their assembly mating skills and not their sketching or modelling skills. This experiment only involved adding mates, excluding other assembly activities (e.g. importing files). The CAD parts were provided

**TABLE 1**. MEASURES OF ASSEMBLY COMPLEXITY

| Complexity | Number of Parts | Average Mates per Part |
|---|---|---|
| Low | 1-7 | 1-1.2 |
| Medium | 8-13 | 1.2-1.5 |
| High | $\geq 14$ | $\geq 1.5$ |

in a single assembly file, such that when opened in the software, parts are already in the correct positions. Figure 3 shows how the CAD file would look once opened in the software. While there are no existing mates (Fig. 3a), parts are positioned correctly, relative to one another (Fig. 3b).

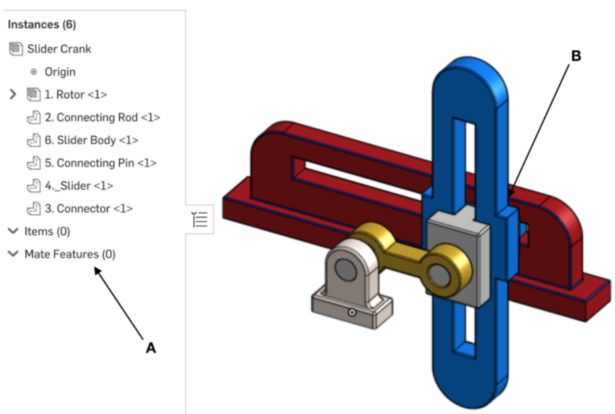


**FIGURE 3**. ASSEMBLY ORIENTATION OPENED IN ONSHAPE HAS AN (A) EMPTY FEATURE TREE AND (B) CORRECTLY POSITIONED PARTS)

The Round 1 assemblies in order of least to most complex were: Quick Return, Schmidt Coupling, and Screw Jack, shown in the left column of Fig. 4. For Round 2, participants were randomly reassigned to groups of 1-4 members and tasked with completing a different set of three assemblies. The second round assemblies in increasing complexity were: Cardan Joint, Manual Clamp, and Hydraulic Scissor Lift, shown in the right column of Fig. 4. It should be noted that none of the teams had enough time to begin working on the Hydraulic Scissor Lift, thus this model is eliminated from further data collection and analysis.

### 3.3 Baseline Task and Score Adjustment

In order to account for the variation in CAD skill levels across the participants, each participant was required to individually complete a baseline task of a basic assembly of six pre-

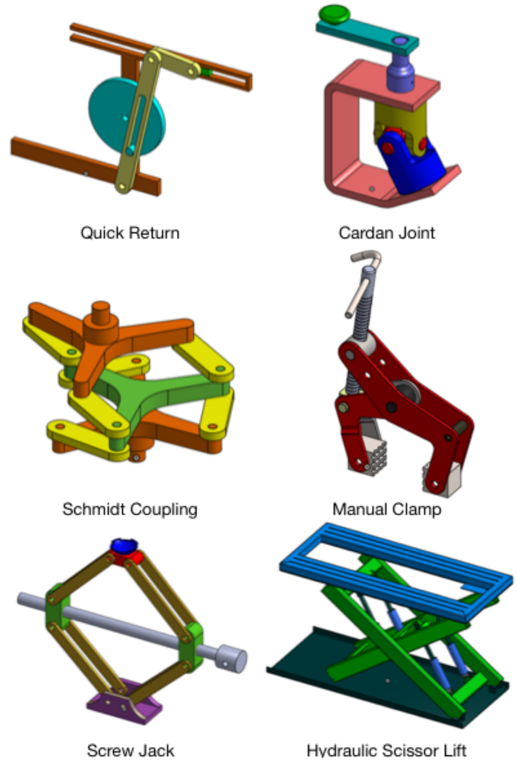


**FIGURE 4**. ASSEMBLY MODELS OF ROUND 1 (LEFT) AND ROUND 2 (RIGHT) FROM LEAST COMPLEX (TOP) TO MOST COMPLEX (BOTTOM)

modelled parts, immediately following the guided training session. Stone et al. employed a similar method to normalize the speed of modelling a single part for each of their participants [4]. The purpose of this task is to generate a time correction factor for each participant to normalize participant modelling skill. The equation for this correction factor is shown in Eqn. (1), where $R_c$ is the correction factor, $t_{avg}$ is the average assembly time across all participants, and $t_{user}$ is the individual user's completion time.

$$R_c = \frac{t_{avg}}{t_{user}} \tag{1}$$

Steiner and Moynihan state that the performance of teams whose members are highly interdependent depends most on the team's weakest link in the relevant skill [46,47]. In this study, $R_c$ is used to measure individual skill. In other words, the lowest $R_c$ of the team is applied to the team's overall assembly time. This assumption was made based on previous observations of collaborative CAD teams, which require high levels of interdependence; teammates must agree on how the assembly moves, which mates to use, and who will mate which components [4].

### 3.4 Demographics

To recruit participants, an announcement was posted in University of Toronto Engineering Facebook and Linkedin groups, aimed at undergraduate engineering students with a minimum of one year of CAD experience. Interested and qualified participants then completed an initial Google Forms survey to collect demographic information. This study and its methodology were reviewed, revised and approved by the university's research ethics board.

Of the 20 participants, 15 identified as male and 5 identified as female. The majority (12 out of 20) of participants were mechanical engineering undergraduate students. Other notable majors included engineering science (20%) and chemical engineering (10%). Demographic information related to CAD experience is summarized in Fig. 5.

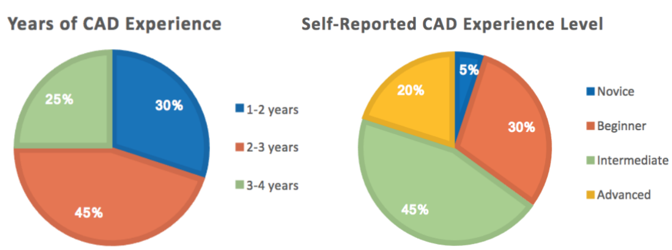


**FIGURE 5.** SUMMARY STATISTICS OF DEMOGRAPHICS

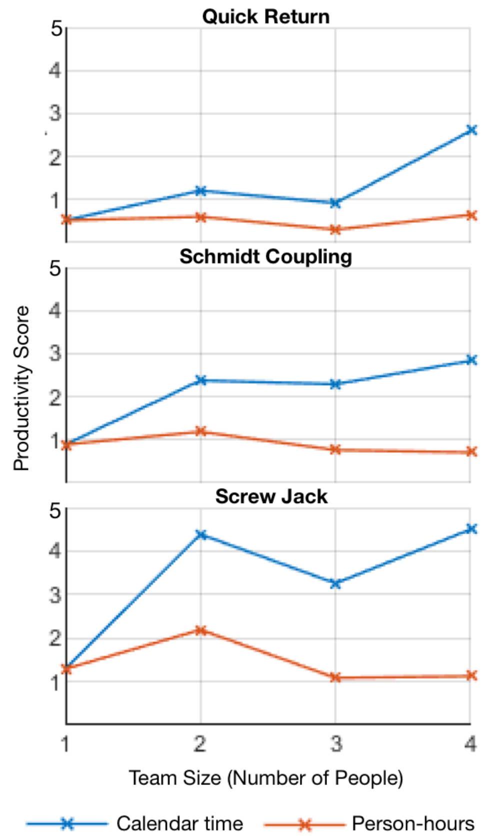


**FIGURE 6.** TEAM PRODUCTIVITY SCORE OF ROUND 1 ASSEMBLIES FROM LEAST COMPLEX ASSEMBLY (TOP) TO MOST COMPLEX ASSEMBLY (BOTTOM)

## 4. RESULTS & DISCUSSION

### 4.1 Team Size and Productivity

In this study, each team is evaluated on their productivity score in completing the assembly tasks. We define productivity score as the number of mates added by each team per modelling time. We consider two different measures of time: calendar time and person-hours. Calendar time serves as the actual elapsed time, equivalent to the amount of time a theoretical client would need to wait for the assembly to be completed, whereas person-hours is the total cumulative time required to complete the assembly, or the amount of time a company would pay in salary costs. Value added per calendar time is given in mates/minute and value added per person-hours is given in mates/minute/person in the team.

Fig. 6 and Fig. 7 show each team size's average productivity score (in calendar time and person-hours) for Round 1 assemblies and Round 2 assemblies, respectively. The Quick Return, Schmidt Coupling and Screw Jack models were assembled by the teams in Round 1 while the Cardan Joint and Manual Clamp models were assembled by teams in Round 2. It should be noted that due to our small sample size (two teams per team size), error bars were purposely excluded and thus no statistical claims are made.

When comparing teams based on calendar time, we can see that multi-user teams consistently out-performed single users. The productivity score in mates/min of 4-person teams was, on average, more than double that of single users.

In terms of person-hours, multi-user teams performed comparably to single users, and in many cases, performed slightly worse than single users. Our findings correlate with the views of Penta, which state that single users perform better than teams, because larger teams require extra communication overheads to coordinate and allocate tasks [48]. Thus, if a company is aiming to minimize labour costs, or if the completion deadline of a project is not urgent, it may be advantageous to hire a single user, instead of a team for CAD assembly. It is notable, however, that across five out of five assemblies, pairs marginally out-performed single users. In other words, we found that pairs exhibit an "assembly bonus effect", where the team's contribution exceeds the combined efforts of each individual [49].

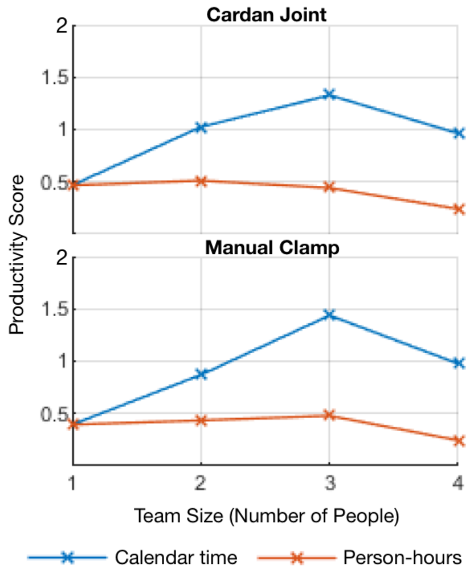


**FIGURE 7**. TEAM PRODUCTIVITY SCORE OF ROUND 2 ASSEMBLIES FROM LEAST COMPLEX ASSEMBLY (TOP) TO MOST COMPLEX ASSEMBLY (BOTTOM)

We expected that the more complex models would take longer to complete than the less complex models. However, the results show that the opposite is true. From the Round 1 assembly productivity scores, we see that teams of every size become more productive as the assembly complexity increases. This effect can be attributed to learning, as participants began with assembling the lower complexity model (Quick Return), then proceeded to the medium complexity model (Schmidt Coupling), and finished with the most complex model (Screw Jack). A CAD learning study conducted by Hamade found that students' CAD skills improved with (1) more time spent using the software, (2) increased familiarity with the user interface (UI), and (3) strategy/planning skills that come with more CAD experience [50]. In this study, students improved faster at the start of the study, and proficiency levelled off as more time had elapsed [50]. Therefore, participants in our study could have increased performance because as they assembled more models, they became better at selecting the appropriate mates, more familiar with the UI, and also more comfortable working with their teammates, having already established a workflow plan. This learning effect may also explain why there is no significant change in team productivity in the Round 2 assemblies between the low and medium complexity model. It is possible that the CAD learning curve began to level off.

#### 4.1.1 Modularity

From previous research findings regarding assemblies, it was hypothesized that multi-user CAD teams would organize via modularizing assemblies into smaller, more manageable subassemblies as a way to delegate work amongst team members. By modularizing the assembly, teams are able to add mates in parallel, which could potentially reduce assembly time and increase productivity. In order to visualize these subassemblies, we display team workflow in a network diagram format. Figure 8 shows the modularity of the Manual Clamp assembly for a single user, 2-person, 3-person and 4-person team. Each coloured node (blue, green, orange, and purple) represents a mate added by a particular team member. The nodes are also numbered chronologically, to show assembly order and periods of overlapping work (e.g. the first mate added is denoted with "1", the second mate "2", etc.).

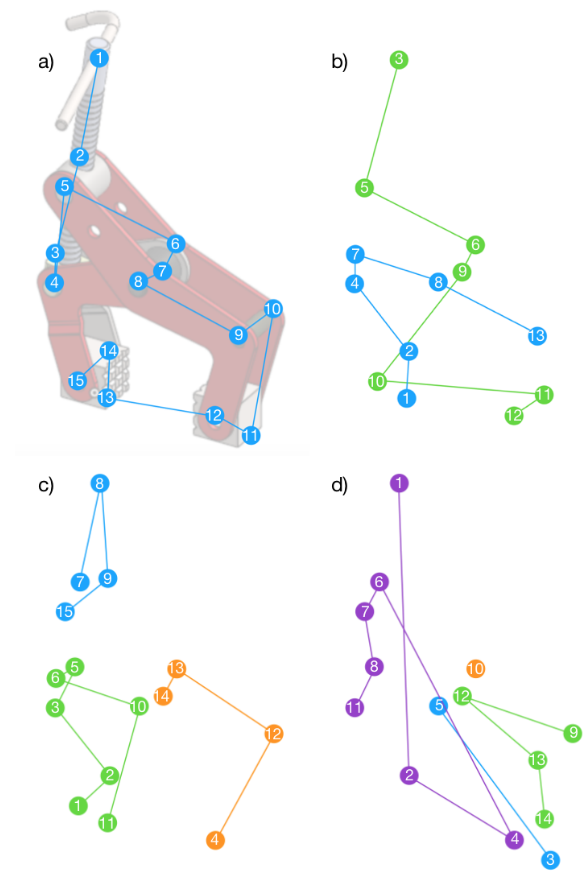

**FIGURE 8**. NETWORK DIAGRAMS OF MANUAL CLAMP ASSEMBLY MODULARITY OF (A) SINGLE USER, (B) 2-PERSON TEAM, (C) 3-PERSON TEAM, AND (D) 4-PERSON TEAM.

As shown in Fig. 8a, single users worked in a generally linear process because they did not encounter the issue of components being moved by other people. Since their workflow was uninterrupted by the actions of other contributors, single users were able to begin assembling at one end of the assembly and follow the geometry of the model.

We anticipated that low performing teams would have a different planning and methodology than high performing teams. The most common modularization style used by nearly all teams was to spatially decompose the assembly by "zone". In this zonal approach, participants selected sections of the model and created all mates that fell within their respective section. "I'll start from the top, you start from the bottom" or "I'll start from the left, you start from the right" were common phrases from the multi-user teams. Teams that chose effective modules worked in their agreed upon zones and had no overlap. The 3-person team in Fig. 8c displays this work arrangement where the geometry was divided into upper, lower left, and lower right modules. On the other hand, the 2-person team in Fig. 8b had an overlapping workflow. From the audio recording, we learned that this team attempted to modularize (with upper and lower modules) but did not choose the most effective subassembly structure, which led to a reduced productivity and low productivity score.

The 4-person team modularized relatively effectively, with minimal workflow overlap. From Fig. 8d, it is evident that the purple user added significantly more mates compared with other team members. This participant was more experienced in CAD than the other three, and likely strayed away from their assigned module to assist the rest of the team. Therefore, it is possible that this team could have avoided overlapping subassemblies if individual contributions were more balanced.

### 4.2 Communication and Team Productivity

It has been well-documented in literature that effective communication is crucial to the success of an engineering design team [51]. We define effective communication as communication that aids in team productivity, such as sharing progress, next steps, allocating tasks, and answering questions, etc. Ineffective communication such as off-topic discussions can distract from the task at hand, thus harmful to the productivity of a team. Stone et al. present evidence that successful CAD modelling teams have a large initial spike in communication for planning, followed by minimal communication throughout the majority of the task, and a smaller communication spike at the end to summarize what was done. On the other hand, the least successful teams communicate consistently throughout the task due to poor planning [52].

In order to identify and analyze communication patterns across different teams, we generated waveform graphs from the audio recordings of each team for each assembly. Figure 9 shows the communication pattern of the best and worst performing team from the Screw Jack assembly task. It should be noted that in this particular assembly, both the best and worst performing teams were two-person teams. Some may contend that it is easier to minimize communication in a two-person team, compared with a larger team with more people to coordinate. However, we find similar trends even amongst larger, four-person teams. Figure 10 shows the communication pattern of the best performing 4-person team and the worst performing 4-person team from the Cardan Joint assembly. Although the best performing team displayed more communication spikes than anticipated, they follow the same general trend of an initial communication spike and substantial periods of silence.

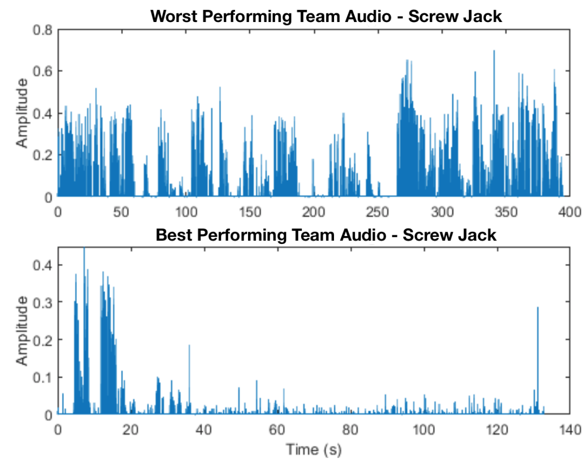


**FIGURE 9**. WORST (TOP) AND BEST (BOTTOM) PERFORMING TEAM FOR THE SCREW JACK ASSEMBLY

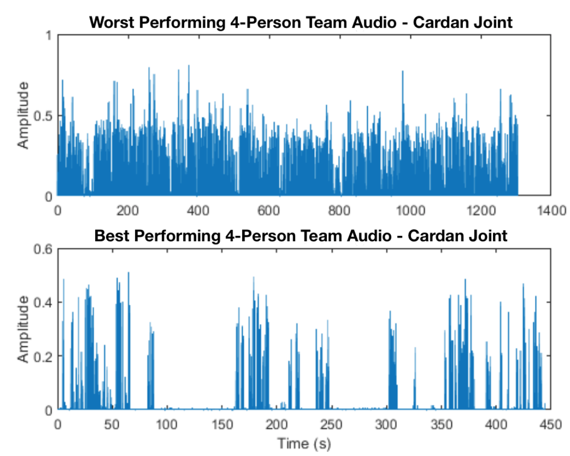


**FIGURE 10**. WORST (TOP) AND BEST (BOTTOM) PERFORMING 4-PERSON TEAM FOR THE CARDAN JOINT ASSEMBLY

From listening to the audio recording, we found that high performing teams initially communicated to build a shared mental model of the assembly, plan assembly order and allocate work. With productive planning, team members felt confident to complete their assigned tasks with minimal direction and input from the rest of the team. In contrast, low performing teams communicated nearly constantly, as team members did not have a sufficient shared mental model. Since members in the low performing teams were unsure of what to do, these teams continued to discuss how the parts should move and which mates were correct throughout the assembly task. As a result, low performing teams did not allocate tasks like high performing teams did.

Overall, we observe a distinct correlation between communication frequency and team performance. The most and least successful team in each of the five assemblies were not always of the same size. In other words, no particular team size exhibited consistently poor or superior behaviour. Every team has potential to communicate effectively or poorly, regardless of its size.

### 4.3 Challenges and Recommendations

From the post-experiment survey and audio transcription, we identify common challenges experienced by the multi-user CAD teams as well as recommendations on how to mitigate these challenges. The first two challenges and associated recommendations are related to how collaborative CAD platforms can improve their features, functionality and user interface. The last three challenges and recommendations are relevant for how multi-user CAD teams should plan, organize and execute their work.

**Challenge 1:** Insufficient awareness of teammates' actions

Participants expressed that it was difficult to effectively communicate to and interpret from teammates which parts the teammates were mating. The lack of clarity caused many teams to communicate back and forth excessively, which took time away from assembling, as one participant explains:

> "It was unclear sometimes which parts the team member was working on, because the interface didn't show the member's activities in detail. The interface would only update when the part design was completed. We could not see who was working on which mates, which parts people were selecting and the real time updates of the part mates."

While Onshape does have a "Follow Mode" feature which allows users to view another collaborator's screen in real time, this proved to be insufficient:

> "Explaining your view relative to the other user was difficult. It was possible to view their [point of view] which helped with collaboration, but was still somewhat cumbersome."

**Recommendation 1:** Implement more collaboration features

In order to improve synchronous collaboration in CAD assembly, we propose three features: ability to view other users' cursors, highlighting the part that other users have selected, and colour-coding mates in the feature tree. Throughout the assembly tasks, participants frequently asked their teammates to what degree they could view each other's activities. Giving users the ability to see their team member's cursors will make it easier to explain each user's relative position in the assembly, as well as pinpoint which person is working on each part. Similarly, it is recommended to enable all collaborators to view the highlighted part that each teammate has selected. This feature is similar to that of Google Docs, where all collaborators can see the text that is selected by their teammates, in each collaborator's unique colour and cursor. Finally, mates in the feature tree should be tagged with each collaborator's unique colour and first initial. This will assist collaborators in quickly seeing who was responsible for each mate.

**Challenge 2:** Component relocation interrupts workflow

During team assembly, parts that one user would be working on would frequently be moved out of view by a teammate, which disrupted the user's workflow. Participants reflected that the actions of their teammates would negatively impact their productivity:

> "It was somewhat distracting having multiple people within a given assembly as for example I would be trying to make a mate and the part that I had intended to select would sometime be moved out of view because of something my teammate had done within the assembly leading to some lost time and a little bit of confusion/frustration."

**Recommendation 2:** Change transparency of first selected part

We propose for collaborative CAD platforms to enable a transparency function, such that when adding a mate, the first selected part becomes transparent. This way, the frequency at which parts must be moved is reduced, resulting in less disturbance to other teammates who can continue to do their tasks. One participant expresses that this transparency function, which is present in traditional CAD, would be helpful if implemented in collaborative CAD.

> "One thing I don't like about this is like, you know, in SolidWorks, when you click for mating, like it'll make the one part you just clicked go transparent. I feel like with [Onshape], you got to move the parts out of the way. I also don't like how it doesn't immediately - like if you haven't clicked on a part already and then click the mate - it doesn't already include that part."

**Challenge 3:** Ambiguity with duplicate components

In the less complex models (i.e. Quick Return and Cardan Joint), all teams relied on the unique part colours and names to identify and differentiate parts. Some of the more complex models (i.e. Schmidt Coupling and Screw Jack) had multiple copies of parts within the assembly. For example, the Screw Jack assembly comprised eight copies of a yellow connecting bar. The lack of a unique identifier for each part made it difficult for team members to describe their activity and to allocate tasks.

> "The Screw Jack had multiple linkages that looked exactly the same which made communicating which part I am working on harder."

**Recommendation 3:** Give each part a unique identifier

One way to reduce the ambiguity that comes with having identical parts in an assembly is to ensure each part in the assembly is unique. This can be done using different colours or renaming parts in the assembly in the feature tree. By giving each part a unique identifier, teams will have an easier and faster time describing a specific component.

**Challenge 4:** Overlapping and duplicate work

A challenge that was commonly mentioned was multiple team members inserting duplicate mates between the same two components, resulting in overlapping work and an over-constrained assembly. If the tasks were not clearly or properly delegated, team members found that they frequently worked on top of one another. In addition to causing annoyance and frustration in some groups, overlapping work is also inefficient since team members must spend time reviewing the feature tree to correct previous mates:

> "It was difficult to see what the other members were doing or what items they were clicking. We had multiple people placing repetitive mates and our system kept producing errors. One other member and I had to keep deleting overlapping mates and try to troubleshoot as the other members kept making mates."

Furthermore, the virtual setting made it difficult to pick up on cues from each teammate. In an in-person scenario assembling physical objects, it is easy to see who is handling an object to avoid grabbing the same one. In collaborative CAD, however, it was common for teammates to select the same part. The following quote illustrates a scenario where each teammate is trying to mate the same two components, because it is unclear which teammate has the component in possession.

> "Okay. One person do [the revolute mate] because I think I keep clicking a part at the same time that someone else is doing it."

**Recommendation 4:** Modularize and create subassemblies

To reduce overlap, it is recommended that teams modularize their assemblies into simpler, more manageable subassemblies. By doing so, team members can be focused on the mates within their respective section and avoid doing duplicate work. One participant motivates this recommendation below:

> "It would have been nice to have subassemblies for each person on the team to work on before combining into an assembly. That would have greatly reduced the overlap and duplicate items in our group model."

**Challenge 5:** General confusion and uncertainty

In our lowest performing team, team members struggled with general confusion and indecision. Individuals who were uncertain about the assembly were overly fixated on small details, rather than focusing on the assembly as a whole. As a result, very little contribution was made by the team, and the team's productivity score was severely impacted:

> "We had difficulties knowing what connections were supposed to be made. Everyone in our team had a general idea of how to put [the assembly] together but struggled to identify the exact/correct connection type. Also, the majority of the team did not want to move on when we got stuck, they wanted to persevere and try to figure it out before moving on."

**Recommendation 5:** Build team with diverse CAD skill levels

We found that teams that were composed of members with varying CAD skill levels were more successful. In these teams, members who were more experienced were able to assist in the troubleshooting process and offer suggestions. Likewise, less experienced users benefitted from the advice given, and could apply their new knowledge to subsequent assembly tasks. The ability to transfer knowledge is a major advantage. As such, it is recommended that teams involving novice designers are also complemented with more experienced CAD users. From the exit survey, one participant wrote that their team had a positive experience because they were able to bounce ideas off of other team members.

> "It was very helpful to have people looking at the same thing you are looking at and being able to provide valuable feedback when you run into issues. At one point I had trouble using a revolute mate and it was taking a while, so I asked my team and they suggested using a cylindrical instead, it then worked."

## 5. SUMMARY OF FINDINGS

Results from our study confirm that teams can complete a CAD assembly in a shorter calendar time than single users. Successful teams allocated tasks that team members executed in parallel, thus minimizing the overall assembly time. While teams were faster in calendar time, evidence was found that in most cases, single users were more productive per person-hour than multi-user teams.

The exception to this trend is with 2-person CAD teams. We found that pairs consistently outperformed single users, across all assemblies. Our findings differ from those of previous studies regarding collaborative CAD. Phadnis et al. showed that single users are faster at CAD part modelling than pairs due to communication and coordination overheads as well as feature dependency [53]. Our study found a slight assembly bonus effect. The audio recordings indicated that teammates in 2-person teams were able to play to their strengths. Each individual was more inclined to add the mates that they knew how to do first, became familiarized with their particular subassembly, and specialized in their own respective tasks. Furthermore, we know from the exit survey responses that many people expressed the benefits of having team members to ask questions to. Many participants found it helpful to have a second set of eyes to locate mistakes and a second person to troubleshoot with and bounce ideas off of. Therefore, participants were slightly more effective in a paired setting, than if they were alone. It is important to note that only pairs exhibited this bonus effect as larger teams experienced more communication overheads, which detracted from modelling time.

Our evidence supports that the worst teams communicated more frequently than did the best teams. The most productive teams communicated effectively, with a large initial spike in conversation for planning, then minimal communication throughout the task, periodically checking in to give progress updates and ask questions, if needed. Teams that displayed constant communication failed to build a shared mental model and struggled to complete tasks independently. Therefore, overheads can negatively impact a team's productivity. Too much communication resulted in lost time.

In our experiment, teams assembled models that ranged from simple to complex. We found that team productivity score results follow the same general trend across all of our complexity levels, which suggests that assembly scales well with complexity. We presume this is the case because mates in assemblies are not hierarchically dependent. When modelling a complex part, a CAD team must place a great deal of emphasis on selecting a proper feature sequence. As a part becomes more complex, more intricate planning is needed and the possibility for errors is increased. In an assembly, however, the assembly order matters less. This means that a team can focus their time on adding mates, rather than determining the "correct" assembly sequence. In fact, some teams reported that they preferred working on the more complex assemblies because the increased number of mates resulted in less opportunities to overlap.

Another key finding from this study is that urgency plays a role in determining the optimal team size in collaborative CAD assembly. From the results, we know that a multi-user team can deliver a completed assembly in less calendar time than a single user. So, if the deadline of an assembly project is quickly approaching, it may be in a company's best interest to enlist a 3- or 4-person team to assemble a model in parallel.

Overall, we identified several factors that can affect the performance of a multi-user CAD team. One of the most important takeaways from our results is that regardless of team size, assembly complexity, and project urgency, taking time to strategize a plan is crucial to a team's efficiency. A successful plan of action can help a team reduce redundancies and avoid duplicate and overlapping work. During the initial discussion, teams should analyze the assembly in sufficient detail such that each team member is adequately prepared to complete their assigned tasks with minimal direction. It is also valuable for teams to modularize their assemblies as a way to delegate work.

## 6. CONCLUSION

Our research investigated virtual student teams collaborating on CAD assemblies of varying complexity. We analyzed audio recordings, team activity, and survey responses to understand how designers can employ collaborative CAD for the assembly phase of CAD design work.

Our results support that multi-user teams can complete an assembly in less calendar time than a single user, across all levels of assembly complexity. We recognize several differences in the behaviour of successful teams versus unsuccessful teams. The best performing CAD teams planned efficiently, modularized assemblies into separate and more manageable subassemblies, executed tasks in parallel, and communicated minimally, but effectively. It was found that communication and coordination overheads detract from assembly time, making teams less efficient than single users in person-hours. However, an assembly bonus effect is present among paired collaborators, because each teammate can specialize in their individual strengths. Teammates in multi-user teams were also able to offer each other ideas and assistance during periods of struggle.

These findings highlight notable implications for design teams and collaborative CAD platforms. By comparing successful and unsuccessful teams, we identify factors that affect the productivity of teams working in collaborative CAD, as well as provide suggestions on how to increase efficiency in future team assemblies. Our research can help design teams improve assembly workflow, task allocation and communication. Finally, we propose new features that collaborative CAD platforms can implement to facilitate designer collaboration in CAD assemblies. Our work supports the claim that collaborative assembly activities have the potential to improve the capabilities of modern product design teams, to ultimately deliver products faster and at lower cost.

### 6.1 Limitations

Our study had a limited sample size of 20 participants. As such, we did not make statistical claims and our results may overestimate the magnitude of the relationship between productivity and team size [54].

We recruited undergraduate engineering students, not professional CAD designers. Although participants were required to have one year of prior CAD experience, only a small subset of our participants (10%) had previous Onshape experience. Realistically, a 25 minute guided training session is not sufficient to fully master any CAD software, even with prior related CAD knowledge. Likewise, very few of the novice designers in our study had previously collaborated synchronously in a CAD system. It may be in the interest of future studies to investigate models assembled by expert CAD users.

### 6.2 Future Work

This research is the among the first to investigate assemblies in collaborative CAD. As such, we identify many areas that can be explored in future work, including but not limited to:

1. Exploring a wider range of team sizes and CAD proficiency levels.
2. Validating the scalability of assembly complexity with a wider range of assembly complexity and number of components per model.
3. Investigating the effect of other mediums of virtual communication on the design process (i.e. video conferencing).
4. Investigating co-located teams, rather than dispersed, completely virtual teams.
5. Considering additional metrics for measuring the performance of a team, such as the quality of the assembly, frequency and magnitude of team conflicts, more collaboration instances, and designer emotions and satisfaction, etc.
6. Comparing teams that model and assemble the parts of an assembly collaboratively with teams that assemble premodelled parts.

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