The Personas of Cloud CAD Collaboration: A Case Study of a Team of CAD Professionals

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***Abstract*—Computer-aided design (CAD) has become a fundamental tool in engineering projects, particularly in product design and development. Recent advancements have shifted CAD systems to the cloud, referred to by us and others as *cloud CAD*, offering a new realm for collaboration in product development projects. The transition to cloud CAD introduces substantial changes to how one might manage product design teams, impacting how design tasks are divided among team members, the choices designers make in undertaking different tasks, and the additional responsibilities team members must fulfill. In this article, we investigate the "personas," described as patterns of activity representing an engineer's roles and responsibilities, that are essential to successful collaboration in cloud CAD. To achieve this, we conducted a mixed-method case study of a self-organized, time-bounded, and geographically distributed team of CAD professionals. This unique setting allowed us to identify and understand the personas that engineers adopt during cloud CAD projects, where the engineers are not constrained to predefined roles and responsibilities. By analyzing CAD user action logs, the final CAD model, and semistructured interview transcripts, we identified three integral personas in cloud CAD projects: the guide, the integrator, and the communicator. We further observed that the emergence of each persona is temporally dependent, varying at different stages of the design process. Our work contributes an in-depth analysis of three personas in cloud CAD, their relevance and benefits to CAD projects, and practical implications for engineering managers to support effective cloud CAD collaboration.**

***Index Terms*—Case study, computer-aided design (CAD), product design, team collaboration, technology adoption.**

I. Introduction

COMPUTER-AIDED design (CAD) tools are used by product development teams to create digital models of parts and assemblies prior to their manufacture. CAD tools were first developed in the 1960s, and CAD competency is now considered a requirement for mechanical design engineers in the workplace. Thanks to new advancements in technology, CAD systems are now moving from on-premise workstations and servers to the cloud, enabling new collaboration methods as well as new ways of creating and managing design files, which result in new tasks and responsibilities that must be performed by design team members.

The adoption of cloud CAD is still nascent among professional design organizations, so most of the existing research on cloud CAD practices has focused on student teams working on well-defined design tasks [1], [2]. In industry, engineering design projects leverage highly skilled teams where effective team building, task division, and role assignment are priorities for the teams' managers [3], [4]. As such, the experiences of engineering industry teams using cloud CAD systems will likely be more complex and, therefore, merit study. In this article, we present a case study of a team of expert designers working on a collaborative project using cloud CAD.

With cloud CAD, mechanical engineering design teams no longer need to be colocated, an increasingly important dimension in the future of workplaces. In addition, instead of working on individual parts—as engineers do in the traditional CAD systems—engineers can work in real time on parts *in context*, where they can maintain an awareness of other CAD parts their teammates are working on. This presents new opportunities for engineering management research as there are no industry best practices for multiperson, collaborative, cloud CAD projects that consider the intricacies of the new systems or the affordances of remote teams using these systems.

As a starting point for research into this emerging topic, we observe a time-bounded, geographically distributed, and self-organized design team working in cloud CAD. The time-bounded nature enabled us to observe the entire CAD design process comprehensively from initiation to completion. This enabled us to study the workflow, decision-making processes, and collaborative interactions throughout the project's lifecycle. A geographically distributed team allowed us to assess how the design team fully leverages cloud CAD benefits, beyond on-premise CAD constraints. Finally, the self-organizing team presented a unique setting to investigate how team members chose to divide and allocate tasks, unrestricted by predefined responsibilities associated with their job titles; engineers had the flexibility to adopt roles on an ad hoc basis, guided by the requirements of the design process. This team management approach offers a valuable opportunity to explore the patterns of activity exhibited by cloud CAD experts when performing design tasks, independent of productive commercial output.

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The aim of this case study is to understand the uniqueness of designing collaboratively using cloud CAD and how managers of engineering design teams can provide better oversight to their teams under this new paradigm. Cloud CAD offers increased benefits for mechanical design engineers, but without understanding the affordances of this new system, design teams may not use the new tools effectively, thereby failing to fully exploit their potential [5].

The rest of this article is organized as follows. Section II presents a literature review on CAD collaboration and the characteristics of geographically dispersed, time-bounded, and self-organized teams. In Section III, we discuss our methods for studying this team's collaboration and communication practices. In Section IV, we document a case study involving a team of CAD professionals that designed a hybrid race car using cloud CAD in a three-week timeframe. In Section V, our results section, we present personas by patterns of activity that represent three roles needed for an efficient team design process using cloud CAD. Section VI explores the significance of the three personas and discusses the difference between cloud CAD and traditional CAD tools in terms of these personas. Finally, Section VII concludes this article.

II. Background and Related Work

In this section, we synthesize the literature regarding cloud CAD collaboration practices and collaboration in geographically dispersed, time-bounded, and self-organized design teams.

A. Cloud CAD Collaboration

The three-dimensional (3-D) CAD is an essential digital tool used by mechanical engineers in the creation, modification, and analysis of a design of a physical product [6]. Traditionally, CAD has been a single-user tool, whereby a single designer works on one local computer system, referred to as *standalone CAD* [7], [8]. To enable multiple designers to collaborate on the same design, CAD files must be shared among them using data management tools. *Collaborative CAD*, also referred to as multiuser CAD, allows multiple designers to contribute simultaneously in real time [8]. One of the notable affordances of cloud CAD is the ability to branch and merge CAD documents, which enables parallel development and streamlined integration of changes within a file [9], [10]. Branching allows designers to work with their own copy of a CAD document without affecting the main development branch [11], [12]. Merging, on the other hand, is the process of combining the changes made in multiple branches into a single target branch. In this article, we denote collaborative CAD as "cloud CAD" because its synchronous features are enabled by cloud technologies.

The existing literature has begun to examine new-generation cloud CAD collaboration [13], [14], [15], [16], [17]; Eves et al. [14] conducted an experiment with engineering students using a commercial collaborative CAD tool and found that, compared with standalone CAD, cloud CAD can increase the awareness of teammates' actions and communication between team members. Stone et al. [13] investigated student design teams of various sizes and found that multiple users modeling a CAD part simultaneously can significantly decrease the overall modeling time but only up to a certain point—suggesting that there is an optimal number of simultaneous contributors.

While prior studies [15], [18] have investigated synchronous CAD collaboration in experimental settings, considerably fewer studies focus on real-life design practices. These studies increasingly leverage CAD trace data extracted from the design software itself; modern cloud CAD tools automatically track and store all actions and edits made by users in the cloud, allowing for the complete reconstruction of the CAD design process, as well as a noninvasive and passive way for researchers to observe designers. Leonardo and Olechowski [19] analyzed a professional design team's CAD trace data to identify different "types" of team members, finding that the analysis of the users' CAD actions can predict those designers' roles and design habits. For example, designers who perform many "commenting" actions are likely to be reviewers of the project. In our work, we expand upon these initial observations of CAD user action types, observing a team with deep knowledge of cloud CAD and focusing on user roles that are crucial for collaborative projects.

Cloud CAD disrupts traditional hardware design by offering unique affordances that revolutionize workflows, enhance collaboration, and drive innovation. Previous research has acknowledged the potential usefulness of branching and merging [1], [2], [20]. Despite the growing body of research on cloud CAD, there is a significant gap in our understanding of how engineers use these tools to tackle real design problems in industry. The existing studies are primarily conducted in laboratory, educational, or experimental settings, which may lack external validity or fail to capture the full richness of real-life collaboration. Furthermore, most studies have focused on novice designers or have relied heavily on CAD log data, neglecting contextual qualitative data, such as the intentions, thoughts, and emotions of designers. As such, there is a critical need for research that can provide a deeper understanding of cloud CAD practices in real-world contexts. Our study aims to address this methodological gap by combining the analysis of collaborative CAD data using cloud CAD software with qualitative interviews of engineers working on a professional project. This mixed-method approach enables us to uncover insights into how engineers use CAD collaboratively, providing a more holistic and nuanced view of how engineers leverage new-generation CAD collaboration tools in practice.

B. Team Organization and Collaboration in Geographically Dispersed, Time-Bounded, and Self-Organized Design Projects

Our case study focused on a design team's collaboration characterized by three distinct aspects: geographical dispersion, time boundedness, and self-organization. These three characteristics form the basis of the context for our study, and thus merit a discussion. Self-organizing teams are comprised of "individuals [that] manage their own workload, shift work among themselves based on need and best fit, and participate in team decision making" [21]; these characteristics are most common in Agile software development teams [22]. Self-organizing teams represent a departure from the conventional approach to product development, where managers lead teams with a command-and-control style, delegating responsibilities to individual members based on functional tasks defined by job titles [23], [24].

As self-organizing teams lack formal mechanisms for assigning and distributing work, researchers have sought to gain empirical insights into how such teams execute roles and responsibilities. Hoda et al. [25] interviewed Agile software developers and found roles crucial to the success of self-organized software development teams, which included among others: the Mentor, who provides expertise in Agile best practices and guides the team in new projects; and the Coordinator, who facilitates collaboration between the development team and the customer. Hoda et al. characterize these roles as "informal, implicit, transient, and spontaneous," highlighting that roles are not formally assigned based on job titles or predefined responsibilities, and team members may adopt or relinquish these roles as project needs evolve. This view is supported by Chen and Lin [26], who emphasize the significance of considering the temporal dimension of team member roles, stating that it is crucial to "assign the right team members to the right tasks at the right time."

Time-bounded collaborative projects involve a group of individuals working together on a specific project within a limited amount of time [27], [28]. The condensed deadlines demand a heightened sense of urgency, leading to rapid decision making, effective problem solving, and collaborative teamwork, thus posing a distinct challenge compared with the traditional development teams [29]. In time-bounded design projects, efficient communication is particularly crucial in the early stages when the goals and tasks of the project are not clearly defined [30]. The condensed nature of these projects also calls for streamlined team formation [31], [32]. As in self-organizing teams, team members are assigned tasks as needed based on individuals' skills and interests. This approach enables a more flexible working process, which is beneficial for the project's fast-paced environment [33]. However, the self-directed task allocation can cause miscommunication and confusion [34], prompting the need for one team member to take on the role of the project manager (whether self-appointed or formally assigned), to facilitate the task allocation process [35]. Project managers play a crucial role in successful self-organized, time-bounded teams, especially when teams are large (five or more members) [36].

Geographically distributed projects operate similarly to colocated projects but with greater reliance on virtual platforms for communication and coordination between team members. The lack of ongoing conversation in a distributed setting can exacerbate misunderstandings or the misalignment of ideas. To mitigate these types of conflicts, it is important to strike a balance between synchronous and asynchronous modes of communication [37]. In distributed projects, opportunities for face-to-face interaction are limited, so teams tend to communicate asynchronously. Previous work has discussed that asynchronous tools (e.g., email) are useful for conveying technical information, whereas synchronous communication technologies (e.g., video conferencing) are more suitable for enabling rich and interactive discussions that promote understanding and agreement among participants [38].

TABLE I
STUDY PARTICIPANTS

Code	Project Sub group	Years of Product Y Experience	Years of CAD Experience	Previous FSAE Experience
B7	Suspension	8	2.5	Undergraduate FSAE experience
C3	N/A	8	5	None
D1	Suspension	10	2.5	None
F10	Driver Safety	15	5	Mentored FSAE teams
H2	Aero	42	5	Mentored FSAE teams
K6	Driver Safety	11	4	None
J5	Driver Safety	5	0.5	None

Each of the seven participants was randomly assigned an alphanumeric code for anonymity. Of the seven interview participants, only one was a woman.

Previous research has highlighted the unique characteristics of self-organizing, time-bounded, and geographically distributed design projects, including informal leadership, the need for efficient team organization, and the sense of urgency from time pressure. In these unique team contexts, members' roles and responsibilities differ from those in traditional design processes. While these insights are valuable for our study, the extant literature on collaborative practices in self-organizing teams focuses predominately on Agile software development and excludes hardware designers working with CAD. We contend that the uptake of cloud-based CAD tools will extend a similar working style in the hardware development domain and hold the potential to shape the future of CAD collaboration. Our case study aims to contribute to the understanding of successful team functioning within this context.

III. Methods

The research team devised a mixed-method approach using the case study approach [39] to study a remote professional design team within a large organization working on a time-bounded project. The design team's project objective was to design and digitally model a hybrid electric vehicle that could compete in the formula SAE design competition.

The mixed-method approach allowed for the triangulation of data from multiple sources, which consisted of the CAD file output of the design process, the backend data analytics, and interview transcripts. By combining quantitative CAD log data analysis with qualitative insights from interviews, we can achieve a more nuanced understanding of the design process and team dynamics. We first performed exploratory data analysis using the backend analytics to understand the volume of design work performed as well as the individual contribution of participants. This baseline understanding of design activity informed our subsequent interviews with the project participants.

Of the 13 total project participants, seven participated in semistructured interviews (see Table I). The initial questions concerned the project's management and issues faced by participants. The interviews, which lasted about an hour on average, were conducted on Zoom and transcribed automatically using

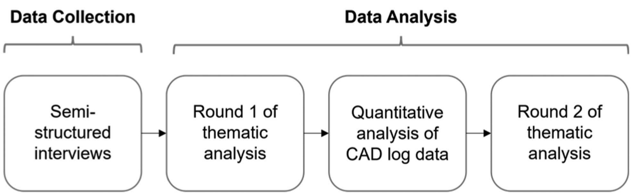

Fig. 1. Overview of research methodology.

Fig. 2. FSAE cars are developed by student teams in preparation for the competition (left), the car is largely built around a welded chassis (right). Sources: University of Toronto Alumni News and University of Delaware.

the same platform. Ethics approval was received for the study from our institutional Research Ethics Board.

After the interviews, two researchers collaboratively conducted the first round of thematic analysis using the interview notes and transcripts to explore themes discussed by the participants [40]. Per our mixed-method approach, we analyzed the CAD log data to validate interview findings by better understanding the following questions.

1) What design actions (modeling, branching, merging, and drawing) were taken by individual team members?
2) Which individual designers were active at specific points during the design process?
3) When each design action was taken during the design process?

Then, we conducted the second round of thematic analysis (i.e., axial coding), revealing four themes, which are the three personas and their temporal order. Fig. 1 summarizes the stages of our research methods.

In total, the research team analyzed 8 h of interviews, 38 pages of interview notes taken by 3 members of the research team, 2 presentations given by the project lead to the organization's staff, and 4 datasets detailing the design actions taken by each project participant (totaling more than 100 000 actions).

IV. Case Study

Company X is a producer of CAD software. One of their software offerings, Product Y, is a cloud CAD platform, designed to run completely in the cloud; this key feature enables collaboration across physical boundaries and devices. Due to this advantage, Product Y also offers data management features that are outside the capabilities of most traditional CAD software, such as versioning (saving iterations of the same design), branching (working simultaneously on multiple versions of the same design), and merging (integrating different branches or changes into a single, cohesive version).

Over the course of the summer of 2022, ramping up over the past three weeks of July, 13 employees in the education division of Company X were involved in a design challenge to model a car that could compete in the Society of Automotive Engineers' (The Society of Automotive Engineers is now known as SAE International.) Formula SAE (FSAE) undergraduate competition (see Fig. 2 for typical FSAE car builds). The objective of the challenge was twofold: to design a model that could be used as a marketing tool to undergraduate engineering students and to win the annual internal design competition organized by Company X.

A. Team Formation

To begin the challenge, one employee (who we label B7, see Table I) sought out interested participants on the company's internal messaging platform. The intention of the message was to gauge the interest of people at the organization to determine if the project scope was feasible given that they would be working on the project outside of their normal work hours. After getting some interest, B7 set up a project workspace in Product Y and invited some of the interested participants to join. The participants mostly emerged from the same department as B7, which included executives, engineers, curriculum development specialists, and interns.

B7, who had been involved in the FSAE competition as a student, acted as the project manager and established an overarching rule for the project: their design process would be as close as possible to that of an undergraduate design team. Simulating an undergraduate team's process would help the final design be representative of a typical FSAE project, an attribute that would be helpful in using the eventual CAD model as a marketing tool. This rule meant that primarily off-the-shelf components would be utilized, and the team would start the design by adapting a chassis that was already tested. As FSAE university teams have only one school year to build a new car, they typically reuse the frame from the previous year and buy off-the-shelf parts.

In this case, the design team acquired a chassis from an FSAE team in a university nearby through their network and imported it into their design file. Choosing a chassis sets a major constraint for the design of an FSAE car as all other parts of the car are erected on the chassis. Next, B7 created *master sketches* (i.e., 2-D sketches that act as a reference point for the design of other features) of the chassis and a free-body diagram of the driver's dimensions as a guide for other participants' design work. The sketches were mostly taken from the FSAE rulebook, a 139-page guide with regulations that affect design decisions (see Fig. 3 for an example of the guidelines).

B. Project Intensification

In the first week of July, it became apparent that the team could put this design project to double use and submit their FSAE model as a part of the company's yearly internal design competition. Their division had won the previous year, and they felt they had a good chance to win again. Participation in the

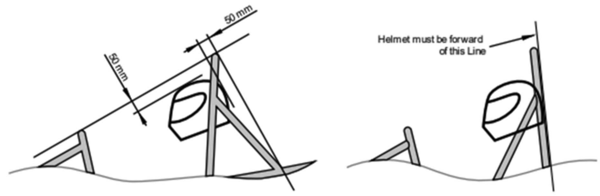

Fig. 3. Excerpt from the 2023 rule book for the FSAE competition showing guidelines for the helmet position relative to the car's chassis. Source: SAE International.

competition imposed a deadline: the design had to be ready in three weeks. This re-energized the team.

B7, who had the most FSAE experience, divided the participants and responsibilities into four teams largely mirroring the major components of the car: Aero, to focus on the aerodynamic aspects of the design; Driver Safety, for the seat and driver interfaces; Suspension, for the wheels and its connection to the frame; and Drivetrain, for the car's movement. Within each team, there was a range in the number of participants: the smallest team (Aero) had only one active member and the largest team (Driver Safety) had up to four members.

Each participant was free to work on the team of their choice. To initiate this phase of the project, there was a meeting of all participants where the teams were self-selected (see Fig. 4 for the timeline of this active phase). In the days after, each team also had a meeting with the project manager (B7) to better understand their individual roles. At the end of the second week, there was a group check-in meeting to assess the team's progress.

As the CAD file was shared with all participants through the cloud CAD platform, they were free to work on it at any time. It was common for teammates to work on the document simultaneously. Within the project workspace in Product Y, the frame was imported into a shared tab for creating parametric models. Teams also had their own tabs where they could work on the part and assembly models for their subsystems. Not all the CAD work involved modeling from scratch; participants were adept at finding CAD models for off-the-shelf parts they introduced into the design, which helped the project move along faster.

As the model became more complete, participants soon realized that, for unobstructed visibility of the parts they were modeling, they needed to hide the parts their teammates were working on that interfaced with their part. Hiding parts in Product Y affects all instances of the model within the same branch, so this was disrupting the modeling work of their teammates who were working on the same shared model. Subsequently, members of the team chose to create individual branches in order to hide parts and not disrupt the work of other designers. As a result of this disruption and to prevent others as the model grew, the project team enacted the following design rules specifically for the project.

1) As soon as a part was interfacing with another, a branch should be created so the engineer could work independently without interfering with the other part.
2) Each participant should merge their branches back into the master branch at the end of every week.
3) When modeling parts of the car, each part should use the frame and master sketches as references.

C. Assembly

Due to the ad hoc nature of the project's design process, there was no agreed-upon assembly phase; each participant was responsible for coupling the parts they had designed to the car model assembly. This meant that all the participants had to work on the CAD file at the same time, and the software became slow as a result. At one point, B7 deleted the shared tab (where the frame was kept) in an attempt to remedy the lag issue, but this was to no avail.

Otherwise, most participants recalled a smooth assembly process, thanks to their usage of the chassis and sketches as in-context references. Parts and subassemblies were assembled quickly, a departure from typical CAD assembly teamwork [18], except for the battery box, which interfered with other parts. The designer of this box had joined the project late and was likely unaware of the design rules.

However, B7 recalled the pain points of some of the assembly work. For example, parts were not grouped into subassemblies before joining them with other parts of the car. This meant that the subgroups (e.g., the Suspension) could not be highlighted separately. Grouping by subassemblies before joining into the top-level assembly is a CAD best practice as it provides hierarchical organization and allows for exploded views of the subassemblies.

V. Results

In this section, we present the four themes from our case study. The first three themes represent distinct patterns of activity exhibited by project participants, portraying personas that engineers may adopt at different stages during the design process using cloud CAD. In addition, these personas are not mutually exclusive; one or many engineers may demonstrate several personas simultaneously. The fourth theme describes the temporal nature of the personas. Below, we discuss evidence from the case study to support the emergence of this persona framework.

A. Persona 1: The Guide

The *guide* is a design team member who demonstrates competence in mechanical design quality by directing the team in part and assembly modeling. Teams of mixed skill are prevalent in mechanical design practice, where team members have various levels of expertise in engineering, mechanical design, or CAD. In this project, some participants—at various times during the project—assisted other team members in technical tasks. The participants who exhibited this persona, which we term the *guide*, showed good design practice as well as engineering knowledge and shared their expertise with other participants. Through our analysis, we found that the designer who takes on this persona contributes most of the sketches in the CAD model.

At the start of the project, B7 identified the need for 2-D *master sketches* to drive the CAD work. Having the most FSAE experience on the team, they acted as a *guide*, as they knew the

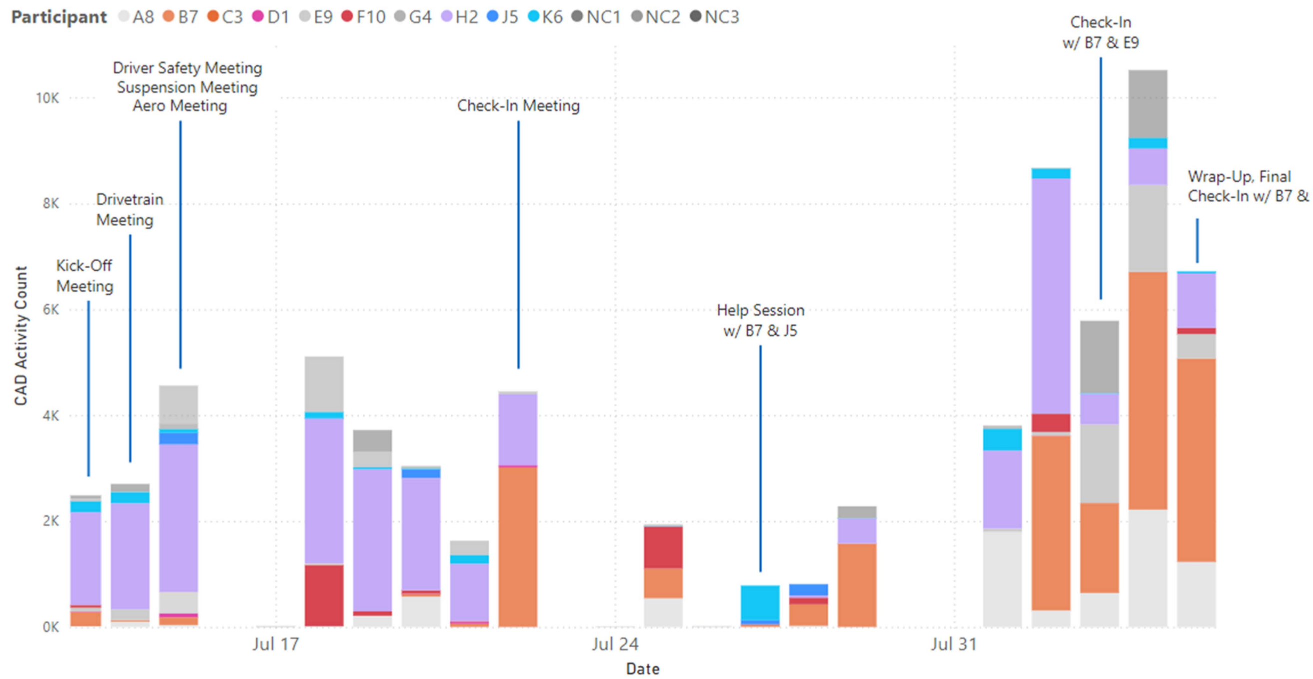

Fig. 4. Design activity∗ during the course of the project. Each color represents a designer who took part in the project and is shown in the legend. The designers labeled A8, E9, G4, NC1, NC2, and NC3 did not participate in our research interviews and are represented in shades of gray. ∗ Product Y records each action taken by participants who have access to a design file, including feature or part edits, translation of parts, branches, merges, and even login sessions. The actions can be downloaded as an audit trail that captures all design activity that occurs in the software.

most about the FSAE rulebook to implement its rules. These sketches, as well as the frame, served as the foundation for the rest of the project, which were vital to team members, such as D1.

"[B7] sent us the rule book, and it's like hundreds of pages. And so, I tried to look through it. But then, eventually, I kind of landed on … I hope someone else is [doing this]. One day I went into the assembly, and there were some master sketches, so someone had sketched out some of the rough envelopes of the final car, like where the driver would be and where the wheels are going to go and then the frame. We actually borrowed the frame from somebody like [a nearby university] or some other team. I think we had started with their frame. We were kind of modelling around that, so that set some of the guidelines."

For large cloud CAD projects, a part or feature must act as a common reference point between collaborators. The *guide*, a knowledgeable designer, established these reference points from which team members can develop in-context elements that help the design evolve. For this project, the master sketches further aided the team during their assembly process as parts made with the same reference could be mated with ease.

Apart from deploying sketches for references, the FSAE project also highlighted some key attributes of a *guide* that are accentuated by cloud CAD: their usage of *black box sketches* with assemblies. *Black box sketching* is defined here as CAD modeling that is done quickly with the intention of later changing or finalizing parameters, usually performed as a part of ideation. For example, when modeling a car, the specifications of the battery may not yet be established, so a cube may act as a placeholder in the model until the final dimensions for the battery are decided, and the modeling of other parts can continue in parallel, without the risk of interfering with the battery geometry.

When design teams use standalone or distributed CAD systems, engineers usually design the individual parts and then insert them into the assembly in a separate file to see how their part fits with the rest of the model. With Product Y, multiple engineers can use black box sketching to define the 3-D space that each of their parts needs to fit into. This can speed up the process of team product design considerably by helping engineers define the dimensions of intersecting parts, ultimately avoiding later conflicts and improving the assembly process.

During the FSAE project, B7 and A2 took on the *guide* persona, using black box 2-D and 3-D sketches to quickly determine the design space they had to work with. When two or more engineers had intersecting parts, they could quickly define the relative design spaces for their parts as well as their assembly configuration, and then return to individual CAD work.

B. *Persona 2: The Integrator*

The *integrator* is a member of the design team who demonstrates competence in cloud CAD software tools by using its functionality to manage the growing complexity of the design model. Over the course of typical mechanical design projects, the size of the design file grows with the addition of new features. In CAD systems, these increases slow down the design work as the increasingly complex feature tree gets continuously rendered by the engineer's computer system.

In the conventional systems, these instances of speed reduction happen to individuals working independently. Product Y is

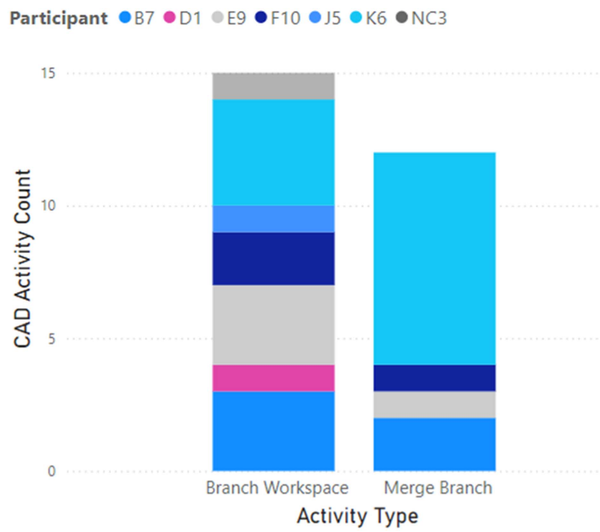

Fig. 5. Number of branches compared with number of merges. Each color represents a branch or merge action performed by a different team member.

cloud native, so during this FSAE car design project, each engineer was accessing the models and assemblies over the Internet. As the project's complexity grew, the whole team experienced a significant reduction in speed. Each member was working on the same document, with each part referencing the car's chassis. At one point, the system's lag rendered the document unworkable for all the designers.

The main culprit for the lag was the number of branches. The designers on the team were chosen to branch to explore novel ideas independently of the team. Also, when some members of the team discovered an incorrectly designed part, they would create a new branch to redesign the part. This led to 15 branches, of which the designers could not keep track.

K6 described an instance of this: "I particularly remember working with [F10], where [they] were working in a branch, things were updated in a different branch but [they] hadn't merged changes." These instances of workflow interference meant that engineers were working with different and potentially conflicting versions simultaneously. Although the majority of the team were experts at using CAD systems and Product Y, they did not have equivalent experience working on cloud CAD design projects with large teams.

More importantly, some team members did not merge their branches back into the main design or communicate these changes to the rest of the team, behaviors that are known to cause conflicts in software development teams that use branching and merging technologies [41]. With cloud CAD and the growth of model complexity that happens throughout the design process, there needs to be a member of the team responsible for merging branches back into the main file. We term this persona the *integrator*. During the FSAE project, K6 emerged as an *integrator*, merging more branches than they created (see Fig. 5, K6's activity is shown in light blue). While 53% (8 out of 15) of which were created in the first ten days of the project, there was generally a long gap between creation and merging since 58% (7 out of 12) of the branches were merged within the past four days of the project.

C. Persona 3: The Communicator

The *communicator* is a member of the design team who demonstrates competence in project risk management by initiating activities geared toward team decision making. Throughout this project, the team grappled with project management decisions. Even though the active team members all had considerable CAD experience, they were new to working with this number of people in cloud CAD. Due to the geographically dispersed, time-bounded, and self-organized nature of the project, their project management strategies were adopted ad hoc. Thus, signaling and communicating issues with the design process became an important part of the project.

The team made use of three types of communication modalities to facilitate their distributed collaboration: asynchronous messages via *Slack* (an enterprise social networking platform used in workplaces[1]), synchronous CAD sessions with team members working on intersecting parts, and Product Y's built-in commenting feature. Each instance of communication—whether messages on Slack, meetings, or comments in the virtual 3-D model—was marked by one commonality: they required an initiator. This persona, which we term the *communicator*, assumed the responsibility of identifying a possible issue and communicating that issue to other people in the team. How they chose to communicate depended on the nature of the issue. B7 explained further:

"[Meetings] were more scheduled. There were some ad hoc [meetings], mostly with a couple of people that either weren't experienced or didn't have a ton of experience with cars in particular, just like messaging me on Slack and saying, 'Hey, I need help with this, and then hopping on an impromptu call to talk through what they were trying to do, and see if I could give them any resources to help them.

Comments were more handy in terms of, 'I've designed a part, let's talk about does this edge fit, or into the whole assembly? Does this kinematically work for the rear drive train, etc.', like calling out explicit points, whereas most of the slack communication was, 'hey can you hop on a call to help me with this', 'hey do you have some reference material for the gearing of an electric motor'. It wasn't really 'hey, here's a specific thing I want to call out about a design; do we need to change it?' that kind of thing."

Synchronous meetings were mostly used for high-severity issues, as they took time out of the participants' work schedules. However, as H2 articulated, when the *communicator* was not able to organize such a synchronous meeting, problems arose.

"[A8] didn't start designing on this project until right at the end [...] which caused problems. We didn't have time to interact and say, 'Hey, that battery box is interfering'. The other aspect of it was, we were trying to get this done in a very restricted timeframe, and so what normally we would have sat down and

1.[Online]. Available: https://slack.com/

TABLE II
COMMUNICATION TYPE AND PROJECT MANAGEMENT

Communication Type	Severity (To Project)	Scope or Range	Decision Type
Slack messages	Low	Wide	Process-related decision, large number of people
In-model comments	Medium	Limited	Artifact-related decision, small number of people
CAD sessions (with audio and video)	High	Moderate	Complex decision combining artifact and process, any number of participants

talked together as a team or as a group to say, 'Gosh! What should we do?' we just said, to get this done [do it this way]."

During the project, the three communication avenues were used in tandem, affected by the severity of the issue and the scope of information required to resolve it (see Table II for a breakdown).

While the *communicators* used all three communication types to initiate collaborative work depending on the severity of the issue, there was a defined order for decision making: smaller decisions, often involving two people on artifact-related issues, were facilitated by the comments; decisions involving a larger number of people, such as general instructions for design, were resolved on Slack; and complex decisions required a synchronous meeting. This finding corroborates others in the literature about the benefits of synchronous technologies for promoting agreement among participants [38].

In conclusion, during cloud CAD projects, the three personas are exhibited continuously. Members of the design team default to a participant nonpersona (shown in white in Fig. 6) where they simply carry out their design tasks. As they become more actively involved in the collaborative project, they acquire one of the *guide*, *communicator*, or *integrator* personas—with the intensity of the persona increasing with more activity. The personas also present in an order across the timeline of the project, with participants changing their personas (or developing hybrids) to match the attributes required for specific collaboration tasks. We present a conceptual illustration of the personas for a hypothetical five-member design team in Fig. 6.

VI. Discussion

This first-of-its-kind case study describing a professional-like collaborative CAD project revealed a number of phenomena worthy of discussion. It should be noted that the participants in this case study are leading adopters of cloud CAD—due to their employment at Company X—and the CAD skill level of certain members of the team is considerably advanced.

First, we discuss the significance of the three personas and their relevance at different stages of the design process. Second, we discuss the challenges in cloud CAD adoption by design teams steeped in knowledge of traditional CAD tools and how these personas evolved in response to those challenges.

A. *Significance of the Guide, Integrator, and Communicator*

Our study found three patterns of activity that team members embodied—which we call "personas"—that were integral to the execution of the design project. These personas were not fixed roles, but rather dynamic and flexible, allowing individuals to assume different personas at varied stages of the project; this flexibility was enabled by the project's self-organizing nature. Our findings align with the previous literature that suggests that a moderate level of role ambiguity—defined as the lack of job-related information (e.g., assignments, responsibilities, and expectations)—can enhance project performance, allowing team members to be adaptable and take on responsibilities as they see fit, while still maintaining clarity and trust within the organization and structure of the team [42]. In this section, we discuss the importance of the personas identified in our study and highlight how the inherent ambiguity of the self-assigning aspect was integral to the project's success.

1) Guide, at the Beginning of the Design Project: Product development teams comprise designers of varying expertise levels. As described in Section V, expertise in mechanical engineering design and previous experience in the design of FSAE vehicles played a role in the present case study. We observe similarities between our criteria of expertise and those used in the literature, such as Mosborg et al. [43] who identified experts as those respected by their peers with years of experience in the field. At the onset of a design project, the tasks required for project completion need to be defined [3]. This analysis is typically performed by the person with the most design expertise, as they would know the tasks that need to be completed and the most efficient way to do so. Thus, we would expect that the guide persona is typically exhibited at the beginning of design projects. It is important to set up a project correctly at the onset, as the cost of changes increases with progress.

In addition, not having a consensus on the modeling practices of the team can be a cause for conflict. C3 remarked that during the project, some of the team members were concerned about different engineers designing parts using different standards and potential issues that could be the result of that. In self-organized projects, particularly when condensed, there is little oversight and team members are largely responsible for reviewing their own work [44]. This can cause design issues that may be difficult to rectify in the long run. From a managerial perspective, it introduces uncertainty about the quality of the design work.

With cloud CAD, there is a need and an opportunity for better guidance in design projects of this kind, particularly at the early stages of the design process, to ensure design quality in the long run. Managers can designate a person with considerable experience in the subject matter of the particular design project as the guide. Their roles could include the production of master sketches that form references for subsequent design work; the

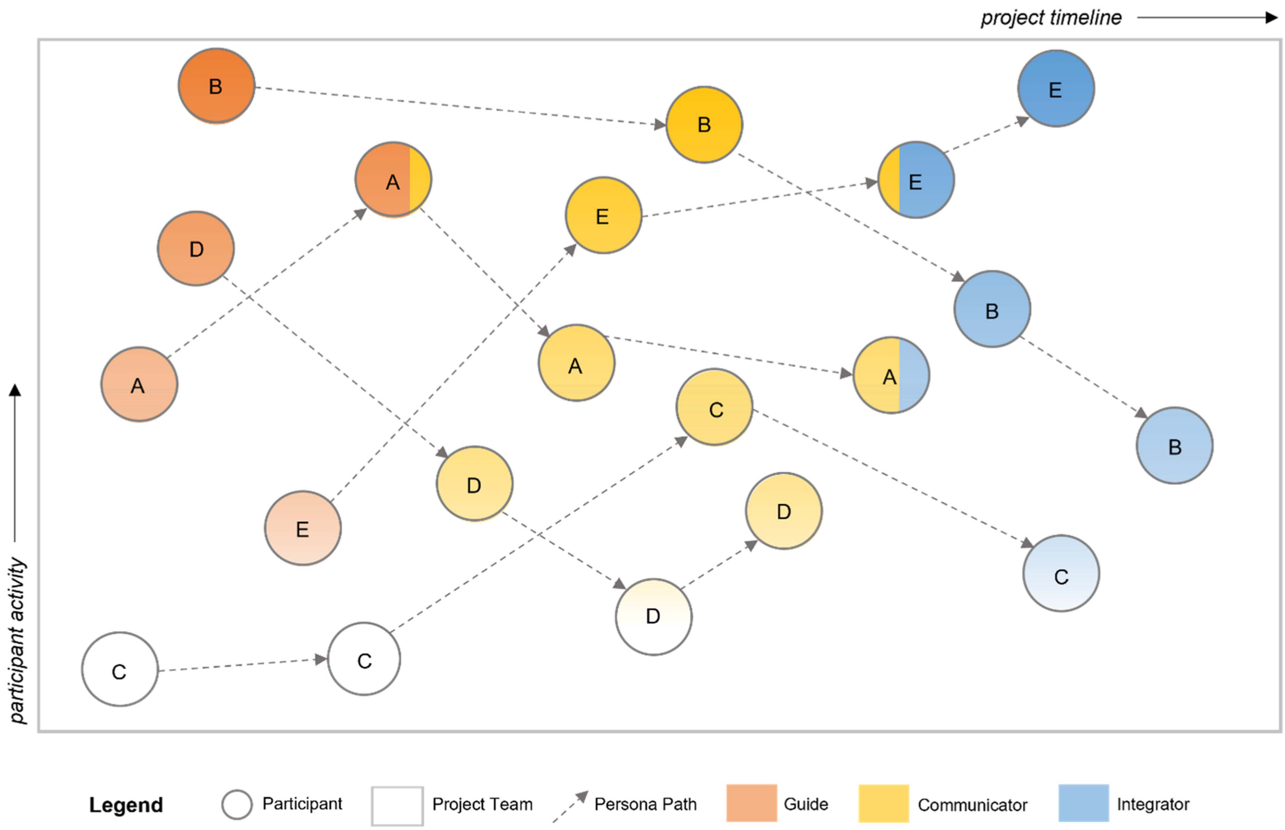

Fig. 6. Conceptual illustration showing the personas of cloud CAD collaboration in a hypothetical team of five designers (A–E). As individual activity wanes or improves during the design process, the personas get weaker or stronger, respectively.

assignment of team members to different design tasks; or leadership at design reviews where members of the team can shadow the guide within the same design model.

2) Integrator, at the End or Inflection Points During the Design Project: Using cloud CAD, the FSAE team's engineers were able to contribute to the project in parallel using the branching and merging mechanism. As the design project progressed, more branches were created, but most merges (7 out of 12) did not occur until the end of the project. The integrator persona is, thus, critically exhibited toward the end, or at inflection points of the project; for example, merging may occur after the design ideation phase, testing phase, or at the delivery of the final product. Our work supports findings in prior literature emphasizing the temporal dimension of coordination, highlighting that the responsibilities of the integrator intensify toward the end of project phases [45]. Further study on this phenomenon is necessary to determine how this persona is triggered; however, it is possible that in projects like this one—where the assembly of the designed parts takes place toward the end—merging the created branches is necessary for the team to know which parts have been completely designed and ready to be assembled with the others.

Designers utilizing cloud CAD can enhance their design processes' efficiency by adopting branching and merging practices from software engineering. One such practice is the use of pull requests [46]. A pull request is initiated when the developer is ready to have their changes reviewed and incorporated into the main codebase. Then, project maintainers or "integrators" assess the code changes and, if no additional changes are needed, approve the request. Once the pull request is approved, it can be merged into the main branch. A well-established rule in software engineering, aimed at ensuring code quality, is the requirement of a pull Request to be reviewed by two integrators before it can be merged [47]. Other guidelines that integrators follow when deciding when or if to merge branches can include: using automated tools to test the quality of code [48]; prioritizing branches that serve the immediate needs of the project (such as bug fixing); and relying on the contributor's track record to determine how much review of their work is required. These guidelines could similarly help managers of cloud CAD projects select and train integrators.

3) Communicator, Dynamic Throughout the Project: Communication is inherent in any kind of teamwork. As such, the communicator persona is present throughout the project. In CAD teamwork, where interacting parts may be designed by different engineers, communication is necessary for determining the best way to interface the parts. In the present case study, we see the communicator in the mold of an "initiator," someone who proffers an outline to jump start and direct a team on a specific task, as posited by Hilliard [49] who studied communication in project teams. In this manner, multiple communicators are present in most projects.

Compared with the other two personas, the communicator is the least likely to be designated by a manager. This persona relies on members of the team realizing that there is a risk of design conflict and signaling to the rest of the team that a decision needs to be taken. This persona is also dependent on the communication channels that the team adopts for the project.

Finally, the communicator should know the status of any interfacing parts, i.e., whether the parts are ready to be assembled. During the FSAE project, an engineer was designing mounts for panels that went around the frame while F10 was building frame panels for fire safety. The parts had an unintended overlap, so F10 acted as a communicator and arranged for both engineers to have a CAD session to resolve this. They decided that F10 should change the geometry of his panels. This style of design conflict resolution was new for F10, who remarked that the FSAE project was the first time they had to consider the context of the part they were designing, i.e., what other parts or sketches the part they were designing had a relation to.

B. Comparison With Traditional CAD

Our case study examined a design team that collaborated on a CAD project exclusively in a multiuser cloud CAD environment. Consequently, many of the typical design practices and pain points commonly encountered by designers working with traditional CAD systems were not encountered by this particular FSAE design team. In this section, we explore the differences between the CAD collaboration practices observed in this cloud CAD team and the approaches that would have been employed in traditional CAD systems for a similar design project.

When using the traditional CAD systems, most design teams utilize a top-down approach, beginning with a rough, overall sketch of the product, followed by a refinement of each product component by different members of the design team working separately [50], [51]. With their design work done, they then place the designed part models into an assembly of other parts (including those designed by other members of the team). In these assemblies, the original design work has been completed and the parts only need to be coupled together. Thus, traditional CAD work is siloed, and without any interacting designers in the original modeling of the parts, most communication between team members occurs outside of the design tool. While designers may physically work side-by-side, there is no possibility of simultaneous CAD work on the same model.

Compared with traditional single-user CAD, cloud CAD affords more opportunities for team collaboration and communication within design teams. In the current case study, we observed three examples of these opportunities. First, during the modeling process, designers are able to observe their collaborators modeling other parts and adjust their designs if they notice any interference. There is also the opportunity to use in-context modeling—using other parts as references for new features—so that referenced parts get updated with changes to the base part. Second, cloud CAD tools allow designers to place comments on specific part features and tag other members of the team. With these comments, team members highlighted issues or suggestions for the CAD model, which improved the efficiency of the design team as they averted meetings that took time away from design tasks. Third, cloud CAD allows for version control, including branching and merging, where designers could work on different versions of the same model in isolation before recombining. These three features solve common collaboration pain points of traditional CAD teams [52] while enabling new ways of working.

Given that this was the team's first experience with a collaborative CAD project of this magnitude, they were unsure on how to optimally set up the project. Thus, each of the personas emerged as a result of a team member recognizing a potential issue with the team's current design process and devising a way to solve the issue using the CAD tool. On the part of the *guide*, there was the concern that designers who had not previously modeled an FSAE vehicle would not know how to begin. Also, due to the rules of the competition that place constraints on the modeling process, it was important to communicate those rules. Hence, it was important for an "expert" to create master sketches to serve as the initial foundation that other designers could access and use. This situation would proceed differently in a team using traditional CAD tools; the expert might have called a team meeting to share the rulebook or created sketches on paper for the team to use individually. Traditional CAD systems, lacking in-context modeling capabilities, would require more complex collaboration methods.

Among the three personas identified in our study, the *integrator* is the one that emerges most uniquely in the cloud CAD tool context. This distinction arises from the introduction of branching and merging capabilities in cloud CAD systems, which directly led to the emergence of the integrator role. The *integrator's* role is perhaps the strongest signal that, while new technology solves issues, it also creates new ones. While designers use branches to explore new ideas or model parts without the risk of interfering with their teammates, the longer they proceed with the work in their branch, the bigger the difference between their model and the model their teammates are referencing, this introduces the potential for conflicts and out-of-date models, which could require major rework. For a small model, this might not be a significant issue. For complex models with numerous parts and subassemblies, however, this can cause issues when multiple—and possibly conflicting—versions of parts are housed in different branches. In the current case study, the *integrator* emerged to protect against this scenario.

The *communicator* emerged due to the need to manage potential risks in the design project. With the team working in the same design model as enabled by the cloud CAD system, team members can monitor the modeling work of their colleagues and flag potential issues. While the *communicator* persona might be similarly present in teams working with traditional CAD systems, the way this team mitigated risk based on severity via different communication channels appears unique to cloud CAD tools as well as the communication style of the design team. In traditional CAD systems, without the ability to create in-model comments, low severity risks might be discussed using virtual communication platforms, such as *Slack* or *Microsoft Teams* (an instant messaging and video conferencing platform used for professional communication[2]). While this might increase communication speed, particularly for remote teams, important design context may be lost without the ability to show the specific feature of interest in the CAD model.

VII. Practical Implications and Conclusion

Cloud CAD enables increased efficiency and collaboration in product design teams; the personas provide useful schemas for design teams to manage collaborative projects such that the modeling work proceeds as efficiently as possible. The current case study highlights the need for new best practices for these projects. In our view, more research is needed on collaborative cloud CAD projects to establish best practices. However, the current work provides a framework that design teams can use to inform their project management practices before any modeling work is done. While our case study focused on a self-organized, time-bounded, and geographically distributed team in order to study the default habits of design engineers using cloud CAD, the persona framework is applicable to design teams in other contexts using cloud CAD tools. To illustrate this framework, we use the three personas.

First, we focus on mechanical design quality, which should be the *guide's* expertise. The *guide* should help the team determine the constraints that guide their modeling work and how the team intends to structure their design model. They should also decide on how the assembly of the different parts will take place: whether each designer will be responsible for assembling their part(s) or a participant—perhaps even the *guide*—will be selected to do the final assembly. Practical questions that a *guide* may answer are: "Should the main assembly consist of parts in different workspaces or different part studios?"; or "Should the number of features in a feature tree be limited in the shared workspace?"

Second, we focus on cloud CAD software tooling, which should be the *integrator's* expertise. During cloud CAD design projects, teams may face the challenge of isolation that occurs in branches, which can lead to an overall lack of awareness of each other's actions. In order to improve collaborative awareness, the *integrator* should help the team to develop and enforce branching and merging best practices, such as the circumstances under which a branch should be made; when a branch should be merged into the master; how to indicate whether a branch is intended to be merged back; or which design tasks (e.g., experimenting with a new design and fixing a design error) are most suited to a branch-based workflow [53].

Third, we focus on project risk management, which should be the *communicator's* expertise. The *communicator* should help the team establish a tiered system of escalation and determine the most suitable communication channel for each level. In addition, the *communicator* should implement and oversee a system to monitor these risks and ensure they are visible to the rest of the team. For a designer taking on a *communicator* role, essential questions for managing the team include: "What issues pose low, medium, or high risks to successful completion of the project?"; "How frequently should issues and design changes be communicated to the rest of the team?"; or "Which design decisions require involvement from specific team members and stakeholders?"

Perhaps the case study's biggest implication for managers of engineering design teams is the necessity for them to consider these personas when monitoring design team performance. With knowledge of how the personas affect teamwork, managers can provide timely feedback to the team to encourage the emergence of the right balance of personas. For example, a design team with ample capability for the *guide* persona but low on the *integrator* and *communicator* personas might complete the design with the best quality but might have significant issues with the software and only discover significant design issues toward the end of the project.

These recommendations provide future cloud CAD teams with high-level discussion points when initiating and managing design projects. The advantages of our study lie in its mixed-method approach, which triangulates qualitative interview insights and quantitative CAD log analysis, as well as our access to real-world design data. However, a limitation of this work is that it is based on only one case study and may not be generalizable to all cloud CAD teams. As such, further study across multiple design teams is needed to develop universal best practices for using cloud CAD in collaborative projects. Future research could focus on formal engineering design teams in regulated engineering sectors (e.g., civil aviation and medical devices' industries) to compare findings between a stage-gated product development process and the self-organized, time-bound case study presented in this article.

The intention is for designers to improve their efficiency throughout the design process and understand the attributes that facilitate effective collaboration using cloud CAD. Teamwork is prevalent in mechanical design, and as the CAD tools improve, so should design team practices.

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2.[Online]. Available: https://teams.microsoft.com/

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