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A Qualitative Analysis of Collaborative Computer-Aided Design Experiences to Inform Teaching*

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Engineering designers use computer-aided design (CAD) tools to generate complex digital representations of product concepts, an increasingly important step in the product development process. With the advent of cloud computing, CAD has seen a recent transformation towards increased collaboration capabilities. Cloud-CAD enables high levels of collaboration, version management, and the potential for easier iteration. This technological capability opens new ways of working with CAD, and engineering design research has made initial progress in understanding how designer behaviour and design output may be affected by the change. The existing experimental studies lay the groundwork for what we might expect to discover when we observe the use of cloud-CAD in a natural industrial setting. However, the educational implications of this new tool have not been fully explored. In particular, cloud-CAD is conducive to collaboration, an increasingly important yet challenging skill for students to develop. This paper presents the results of a series of exploratory interviews with engineering designers who have experience using modern cloud-CAD for their work. Using grounded theory, we identify consistent themes related to the way designers use these tools. From these findings, we generate both recommendations for the engineering education community and areas of future work. We argue that to maximize engineering trainees' potential, we must update our teaching to reflect the full affordances of the latest technologies, like CAD.

Keywords: computer-aided design (CAD); cloud-CAD; collaboration; education; psychological safety; interviews; industry professionals

1. Introduction

Generating intermediate conceptual representations of designs is a core part of the engineering design process. Sketches and hand-drafted engineering drawings were once relied on for such artifacts, but since its inception in 1969, computer-aided design (CAD) has become one of the most prominent tools used by engineers. For novices and experienced designers alike, digital CAD models have utility not only as a high-fidelity digital representation, but also as a tool for communication with stakeholders, design for additive manufacturing, and the enabling of complex simulation and testing earlier in the design process [1]. However, at the time of inception of CAD, the switch from analog to digital modelling was not seen as universally positive, as some engineering educators worried that their students "will not have their experience of collaborating over drawings with peers and teachers, bouncing ideas off of each other, and soaking in new design approaches and visual thinking. Instead, the new design culture in the classroom may be individual, solitary, and focused mainly on the student interacting with a computer screen" [2, p. 56]. Indeed, traditionally, CAD has been plagued by challenges related to collaboration, integration, and version management, resulting in primarily individualized work with predetermined and static interfaces.

Recently CAD has made its way to the cloud, facilitating a dynamic environment where data-sharing and collaboration are easy, unlocking the possibility of new modes of design [3–6]. This CAD transformation has the potential to address the previous concerns of the individual, solitary CAD design experience, re-establishing the engineering culture of "dynamic minds coming together to solve a problem in the most imaginative and inspired way" [2].

While there is overlap between the affordances of traditional and new forms of CAD, cloud-CAD introduces features that were once foreign to traditional CAD, such as synchronous multi-user editing, advanced user analytics and branching and merging of the design tree [4]. If new CAD tools are taught in a traditional way, learning the standard material is relatively simple through conventional pathways, but it leaves the novel content unexplored, limiting individuals from using the software to its fullest extent. Further, cloud tools open the opportunity to introduce new instruction and learning activities, such as sharing, co-editing, communication and discussion, and ultimately important high-level educational goals like team-

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work and communication [7, 8]. It is time to revisit how we teach CAD.

Our study seeks to gather opinions and experiences of professional engineers regarding their use of cloud-CAD tools. In particular, we seek to better understand how the cloud-CAD tool affects the design process, both for the individual engineer and the team, to better inform how CAD is taught. Ultimately, this knowledge will help prepare graduating engineers to effectively use leading-edge tools as they enter the workforce.

2. Background

2.1 Computer-Aided Design

Computer-aided design (CAD) is a modelling software used by engineers to create digital representations of their designs. These models are used for various tasks in the product development process, including simulations, communication, analysis, generation of drawings and instructions for manufacturing [9]. CAD has become an invaluable tool despite several characteristic drawbacks that hinder the design process.

Traditional CAD software is desktop-limited, requiring a costly license for a user to have full access to available features. Models are often saved on local storage devices or add-on Product Data Management (PDM) software [10]. Change requests or iterations create new instances of the model; as more contributors add to a project it can become difficult to manage who has the most updated model. As depicted in Fig. 1, designs become bottlenecked as engineers must wait for file uploads before adding their contribution.

The recent introduction of cloud-CAD has centralized data storage. Changes are automatically saved to the cloud and updated in real-time, which introduces collaborative CAD capability. Similar to Google Docs, cloud-CAD allows designers access to the same document where they can simultaneously work [4], as represented in Fig. 2.

2.1.1 CAD Education and Training

The literature on traditional CAD education and training is varied and informative as a basis by which to consider cloud-CAD training.

Published in 2009, Hamade conducted a three-year study of 4th year engineering students, seeking to explain differences in aptitude for learning traditional CAD [11]. These researchers identified characteristics of a star CAD trainee as an individual who is technically competent, perceptive, and motivated. These students further exhibit an active, sensory-driven, visual, and sequential learning style. While "soft" attributes are considered in this study, the paper does not consider teamwork, communication, or collaboration, since at the time of publication, these capabilities were not conventionally considered in CAD work.

Huang et al. test the cognitive-apprenticeship strategy in the context of traditional CAD learners [12], a procedure that could be further enabled by cloud-CAD. The authors find that different teaching methods and materials lead to differentiated metacognitive behaviours and different learning patterns. Problem-solving was found to be best enabled via both a tangible 3D printed model and the cognitive-apprenticeship strategy, indicating the importance of a collaborative relationship between teacher and student.

Rubrics represent an alternative method to support instruction. Company et al. present a set of quality criteria for traditional CAD modelling [13]. These rubrics guide CAD trainees to consider quality earlier in their instruction by making expectations explicit. Further work is warranted to understand whether these rubrics require revision to be applicable to cloud-CAD instruction.

Gracia-Ibáñez et al. described the evolution of traditional CAD curriculum in the undergraduate program, putting forth strategies to improve the course deliverables and structure [14]. The authors implemented a two-year undergraduate course that used AutoCAD as their choice of software. Students were required to design parts according to the assigned prompt. As the program continued, the criteria for grading these assignments became more

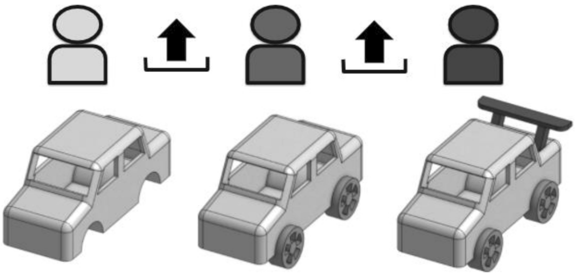

Fig. 1. Traditional CAD requires designers to exchange files before adding their own contributions.

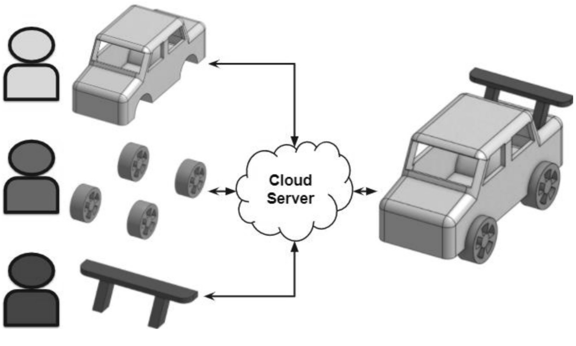

Fig. 2. Cloud-CAD allows individuals to work in parallel and immediately see how their contributions affect the overall model.

intense. The students adapted to these increasing demands, and by the end of the second year, more students passed the qualification exam than in the previous year.

Similar to our paper's goal of drawing from industry experience for implications to design education, Robertson et al. explain the influences of CAD on the creativity of engineering designers [15]. The authors warn that using CAD tools may lead to constrained creativity, arguing that we must not simply focus on the technical proficiency of students' use of the tool but also the development of personal working styles and habits. The dynamic environment of cloud-CAD may not exhibit these same inhibitions to creativity.

Gender is an important lens of analysis when studying spatial reasoning tasks, which are fundamental to the experience of using CAD. In particular, previous studies have shown that men and women exhibit different levels of confidence in engineering depending on the spatial strategy instruction they receive [16]. This study reinforces the need to carefully consider systematic biases in student preparation by proving that a one-day spatial strategy instruction was able to ameliorate gender differences in spatial engineering tasks.

Thus far, the potential for analytics to inform CAD teaching and learning has been under-developed. Xie et al. present evidence of CAD logs capturing evidence of the effect of teaching intervention, as well as the student engagement and iteration patterns, therefore being beneficial to assess learning [17, 18]. The custom-collected CAD logs in these studies are fine-grained empirical data of student activity, analogous to the analytics readily accessed via commercially available cloud-CAD solutions.

This varied set of research indicates that traditional CAD instruction has reached a level of maturity where refinement and incremental improvements are possible. While these approaches focus on traditional CAD, in this paper we aim to establish a first baseline of understanding cloud-CAD.

2.2 Commercially Available Cloud-CAD

Onshape is a browser-based cloud-CAD software. Developed by the same founders of traditional CAD software SolidWorks, Onshape has many commands similar to SolidWorks, primarily in sketch and model creation. Despite having some overlap, the user interface (UI) is different from traditional CAD, with Onshape introducing collaboration features only possible in cloud-CAD architectures.

Features such as versions, branches, and merges expand the capabilities of data management. These elements are seen in GitFlow, a version control manager for code-based work, but have previously been omitted from CAD. When indicating a milestone, a user creates a version, an immutable snapshot of a document to indicate progress, and can use that version to create branches, which are separate workspaces derived from previous work. The workspaces allow for experimental designs without affecting the overall model. A branch can then be merged into the main workspace, becoming part of the central design. These features are integrated into Onshape's internal product data management (PDM) system, which is particularly beneficial for companies without an established PDM.

A feature specific to Onshape's Enterprise account is known as Onshape Analytics. This interface allows users to see detailed reports on their account activity, such as login location, user activity logs, and document history. Additional information includes a complete list of commands that are performed within a document [19].

With Onshape having recently released their Enterprise model for business, more and more companies are beginning to adopt Onshape as their primary designing software, which is why it was chosen as the CAD software for this study. Since cloud-CAD has only recently emerged, engineers who use the software in the industry have learned to use the new features and workflows in an ad-hoc manner. This study takes a closer look at how this process of adopting Onshape has been for users and whether they can make use of the features that promise to improve collaboration.

2.2.1 Initial Understanding of Cloud-CAD

Next, we will review the studies that provide a preliminary understanding of the influence of new cloud-CAD tools. The introduction of cloud-CAD introduces new features, working modes and designer freedoms. Much of the current work in this field relies on experiments, building on previous CAD instrumentation set-ups [20, 21] to incorporate collaboration via cloud-CAD tools [22], probing specific research questions.

Researchers at Brigham Young University have looked closely at how collaborative CAD affects the design process [23–25]. Using a collaborative CAD tool called NXConnect, they perform a series of experiments. One experiment compared the output quality of individuals working on the cloud to those who shared files via email [23]. Teams were given tasks that mimicked a work environment and had to complete them in a specified timeframe. The researchers did not find a significant difference in model quality between those who collaborated via email or cloud-CAD. They did, however, conclude that users on the cloud were more aware of their teammates' contributions and were less frustrated over miscommunications. A fundamental limitation of this study was that participants were unfamiliar with the software prior to the study, limiting their modelling capabilities. Another study presents an analysis of a multi-user CAD design competition [26], concluding that effective communication is a predictor of team success. These studies indicate that performance in cloud-CAD environments relies not only on technical skills but also on social skills, like communication.

Drawing inspiration from the software development field, Phadnis et al. apply pair programming configuration to CAD, which they dub Pair CAD [27, 28]. Pair programming is a common working mode in which two programmers work synchronously on the same code, which has proven to lead to satisfying experiences for learners and higher quality code. Pair CAD is possible because of synchronous collaboration enabled by cloud-CAD, as implemented in an observational design lab. This study presents experimental evidence that working style influences CAD output and that implications established in the pair programming literature express in pair CAD.

Further leveraging the real-time collaboration capabilities of cloud-CAD, Zhou et al. provide experimental evidence that when compared to individual CAD, performing CAD tasks with a virtual partner leads to a greater level of emotion, both positive and negative, for designers [29]. Higher levels of emotion have been found to correlate with higher levels of engagement, which may lead to higher levels of learning.

These studies observe designing with CAD through the lens of controlled environments but have at times been hindered by the participants' limited proficiency in the software. As Atman et al. explore, there is a disparity when observing the behaviours of novices and industry users [30]. For this reason, we will interview cloud-CAD users in industry to have a better understanding of cloud-CAD use in a professional and mature environment. These interviews will provide insights on how to better prepare future engineers.

Although limited to an experimental setting, the studies referenced above highlight the differences between traditional and cloud-CAD. By further exploring software with cloud capabilities, we can gain insight into behaviours to expect in our exploratory analysis of industry professionals.

2.2.2 *Cloud Learning Capabilities in Other Contexts*

While CAD has only recently been developed as a cloud-solution, other fields are more mature in their transition to the cloud. GitHub is a collaborative environment that allows coders to develop their own repositories, share code for review, and coordinate how their contributions impact the overall project [31]. With code management systems becoming more prominent, educators have begun to integrate GitHub into their curriculum. The University of Victoria performed a qualitative analysis on the student experience of GitHub use in their classwork [32]. Students found the software beneficial because they could easily organize their material online and reference from other sources.

Additionally, a few students acknowledged that they had become aware of what their classmates were working on because cloud storage allows for transparency. In another one of their studies, students echoed the sentiment that collaboration should be at the forefront when utilizing cloud software [33]. For coding tasks, cloud-collaboration introduces transparency which allowed students to learn from one another.

While Cloud-CAD is still an emerging software and its implications have yet to be fully explored, these studies on collaborative cloud software preview some of the themes that we may discover through our exploratory interviews with designers from industry.

3. Methodology

3.1 *Grounded Theory*

This research followed the protocols of grounded theory to explore the uncertainties of cloud-CAD. Grounded theory is the method of developing hypotheses or theories from one's own social research [34]. Researchers formulate their hypotheses from a particular set of participants rather than developing theories from a large, general population [35]. The key difference between grounded theory and other methods is constant comparison, in which a researcher is constantly going back and forth between existing literature and their dataset [36, 37]. This process strengthens the foundation of the proposed hypotheses. While the claims developed via grounded theory cannot be said to be representative of the entire population, researchers can next pursue further investigations with more concrete hypotheses [38].

3.2 *Conducting the Interviews*

We developed an interview guide focusing on three topics: general CAD background, learning cloud-CAD, and cloud-CAD in practice. To obtain accounts reflective of how CAD software is used in practice, we sourced our participants from industry engineers, targeting those who use Onshape during their routine design work. These participants were recruited through the authors' professional

Table 1. (a) Demographic breakdown of participants. (b) Demographic breakdown of companies

(a) *Participants*	Total = 12	
Gender	***n***	**%**
Male	9	75
Female	3	25
Age		
21–29	3	25
30–39	6	50
40–49	3	25
Race		
White	10	83
Non-White	2	17
(b) *Companies*	Total = 10	
Characteristics	***n***	**%**
Startup	5	50
Cloud-CAD From Inception	8	80

networks, connections from Onshape customer representatives, and postings on online forums. We interviewed twelve individuals from ten unique companies for this study. Nine of our participants identified as male, and three identified as female; our participants were predominantly white and spanned from early to mid-career professionals. Regarding the companies, eight were startups, five of which have been using cloud-CAD since their inception. To preserve the anonymity of our participants, we present pooled demographics in Table 1.

The research team consisted of three interviewers: one lead interviewer who was responsible for guiding the interview and was present at all sessions, a secondary interviewer who took notes occasionally asking follow-up questions and was present at all but one interview, and a tertiary interviewer who was present for the first two interviews. One to three researchers interviewed one participant at a time via Whereby, an online video conference system. The interviewees did not receive any form of compensation for their participation in the study. These interviews were conducted via Whereby, an online video conference system. Participants were interviewed following an interview guide (see Appendix). The interviews (n = 12) lasted a maximum of one hour, with the average length being 37.4 minutes. We recorded the audio from these interviews and then transcribed them using the automated transcription service from Rev. Each file was reviewed and edited for inconsistencies between the audio and transcripts.

3.3 Transcript Analysis

The transcripts were next imported to NVivo, a qualitative data analysis software. One author then analyzed the transcripts via thematic analysis, encoding phrases to general codes that provided an overview description for the data. For example, the following phrase was coded as 'collaboration' for its references to teamwork and cooperation: "I'll log in and work on something inside of Onshape and tag someone in [a message] . . . then they can check [the model] out on their own time" (P5). Consistent with grounded theory, these interviews were constantly reviewed during the collection process. During the first round of analysis, the general nodes served as a basis for better organizing and understanding the data; these nodes were broad categories covering attitude, learning, collaboration, communication, and data management, all with respect to Onshape. After conducting six interviews, we refined the nodes to be more descriptive and representative of the encoded data. For example, within 'collaboration', the quotes referenced how short spontaneous meetings became the primary interaction method, resulting in the theme *Intermediate Check-ins*. Fig. 3 showcases the map-

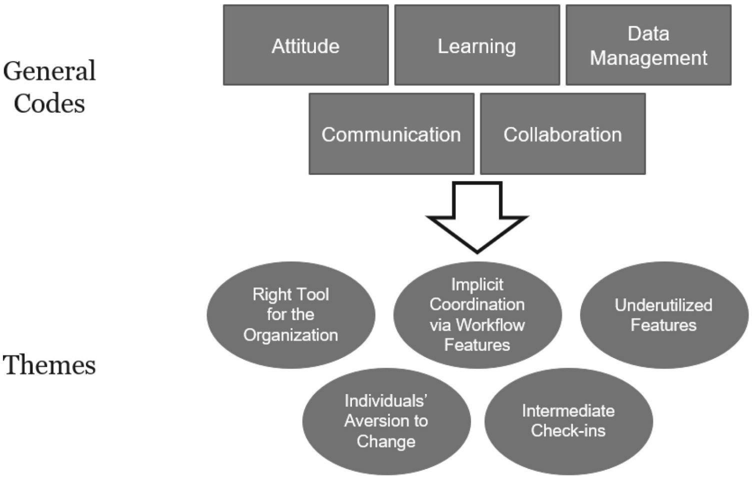

Fig. 3. General codes being translated to their more descriptive themes.

ping of general codes to the themes, identified as *Individual's Aversion to Change*, *Right Tool for the Organization*, *Underutilized Features*, *Implicit Coordination via Workflow Features*, and *Intermediate Check-ins*.

Following iterations of encoding, we reviewed and identified the context in which the themes are most relevant for adoption. We provide recommendations for each context to ensure their needs are met when teaching CAD.

4. Results

This research explores the capabilities of cloud-CAD and how professional designers have adapted to the software. The interviews focused on the specific aspects of how individuals grew accustomed to Onshape and how they used it in their daily operations. Below we will highlight themes revealed by the interviews.

4.1 Right Tool for the Organization

This theme captures the reasoning as to why a company may make the switch to cloud-CAD and the potential implications. Six of the ten represented companies have recently made the switch to Onshape. One participant expressed concerns about whether the software would meet the needs of the company: "Engineers who have spent years using industry-standard software are more resistant to change and are more conscious of the lack of capabilities [of] other software" (P12). As Onshape is still in its early stages, several features are not as advanced as they would be in other modelling systems. Another participant, however, addressed that new software does not necessarily have to be as complex as its predecessor:

> "It is an interesting balance because depending on the work you need to do, you'll need the tool. . . if you design airplanes, you're going to use a different engineering software than if you're designing playgrounds. There's a different set of tools for each of those." (P11)

Legacy data has also become a point of contention for newer users. Companies that have used cloud-CAD since their inception can easily create models native to the new cloud-CAD environment. Older companies, however, encounter complications when transferring legacy data from previous CAD software: "While imports are possible, significant information is lost. This is an issue when new designs are based on older models" (P12). The size and agility of a design team will also influence how quickly the software is adopted. Five of our participants described the fast-moving nature of their companies: "much of what we do is get something that works and then move on to the next pressing project." (P3). In these environments, industry professionals worked independently and on unconnected designs, resulting in little perceived need of advanced collaborative and data management features. Participants expressed that while certain features were underused, they saw the potential to incorporate these features into their workflow as the team grew.

Perhaps the biggest barrier that inhibits widespread adoption of cloud-CAD is the inertia of existing processes and workflows. Having seen little change since inception, some CAD users have developed deeply held assumptions about how it must work, such as the rigid requirement of an on-site server. One participant, however, counters this notion by stating how the reliance on cloud services is not unique to CAD:

> "The world of CAD is quite fossilized around the idea of having data in a server in the closet of your company... All kinds of other business processes are already on the cloud... Every other business system is on the cloud, but for some reason, [companies] are terrified of the cloud and can't understand how CAD could be in the cloud." (P9)

4.2 Individuals' Aversion to Change

Adopting cloud-CAD requires companies to venture into new territory, deviating from the norm. There are promises of efficiency, but the costs are not yet fully understood. An interviewee explained that a coworker expressed concerns over deviating from industry standards and "how a partner in [their] supply [chain] or manufacturing was more familiar with SolidWorks" (P12). These concerns create a paradox in which adoption of cloud-CAD is inhibited by not being typical industry practice, but industry practice cannot change without adoption.

In learning Onshape, participants found many of the fundamental modelling features easy to learn: "[Concerning] all the part modelling, all the sketches, extrusions... no real learning is needed. [The commands] are all very similar [to that of other CAD software]" (P4). Despite the similarities, there were reservations about using newer modelling software. Participants in the 30 and above age brackets had CAD experience ranging from seven to twenty-seven years, and a software change threatens to disrupt their established workflow. P10 described this by saying, "[I'm] 10 years in, and I'm pretty comfortable. I definitely put myself in the category of needing to be convinced that this is worth all the effort of the transition."

Familiarity with the tool is essential to our designers. P9 expressed how a coworker's workflow was disrupted by "the level of granularity of control" not being as high as that in other software. Along with relearning modelling techniques in a new environment, engineers must adapt to the nuances associated with the cloud. One participant noted a clear difference in how age affected the adoption of Onshape at their organization:

> "It was only close to the end of my contract with one client that they hired a more senior engineer, and he was much older. So, he was not used to even the concept of what collaborative CAD was. So, I spent weeks explaining to him that this is possible. Younger interns, many interns that we hired and I trained, immediately understood [cloud-CAD] because they have been using Google Docs all throughout university." (P7)

Interestingly, our three engineers in the 20–29 age bracket were first exposed to Onshape through either school projects or prior work experience.

4.3 Underutilized Features

As previously discussed, the size of the organization appears to affect the widespread use of certain features. Rather than use cloud-CAD tools to exercise control over the process, smaller teams prioritized completing the project at hand in a timely manner, sometimes without a formal process: "I am familiar with the releases, but then I turned them off just because we're in startup mode, and we don't really release things at present because it's just the two of us" (P4). The use of releases creates a more formal process to review, but at a smaller company, this can be easily accomplished through informal coordination.

While releases do not see much use in the beginning stages of adoption, participants see their potential. We see this trend continue with other features, too: "It's not admittedly crystal clear to me exactly the best way to use [branches], but I understand what they are and what they're for" (P10). With cloud-CAD introducing new concepts to CAD, engineers are unsure of the best ways to build a workflow around the associated new features.

Exclusive to the Enterprise users, Onshape Analytics provides a statistical breakdown of designers' modelling activity. While various statistics are provided at the analytics dashboard, the easiest to understand is the amount of time an individual is active on the server. Our Enterprise participants expressed that time was the most useful statistic on the dashboard because it helps distinguish active users from inactive ones: ". . . Let's cut down the number of licenses. And so, one easy thing to do was go through analytics and see who are actually the people that are using Onshape regularly by modelling time" (P8). Beyond this, most were unsure how to use the analytics properly and felt this information would better inform at the management level rather than at the designer level.

4.4 Implicit Coordination via Workflow Features

Teams have used Onshape features to create implicit meanings in their workflow, facilitating communication and coordination. One instance of this behaviour is achieved via versions and releases. In essence, both create snapshots of a model at a specific moment in time, with the latter requiring approval. The use of these features is best described in the following statement:

> "Versioning is something that you might do every half-hour or so. As you're making progress in the design, you hit many milestones, and you take snapshot versions of the state of the document. Making a release is communicating to the team the way that I think about [the model]." (P9)

This mentality was consistent in other companies that used releases as a means of "getting ready to send parts out to vendors" (P1) or "going to send [parts] off to go get created" (P5). The distinction between creating a version and release is simple, but it allows designers to implicitly signal project progression to their teammates. Implicit coordination is also achieved via other features. P11 uses branches "to generate some alternatives. . . until [making] a decision" about the model. Branches are used to experiment in a document by making edits in alternate workspaces without affecting the main branch. There is an implicit comprehension that branches are treated as experimental grounds until they are propagated back into the main branch.

Another feature that influenced the design workflow was the Part Studio, which works cohesively with top-down design. In top-down design, an overview of a system is generated by breaking the project down into its first-level subsystems. From there, each subsystem is further detailed with specifications [39]. This capability is embedded into the Onshape workflow but requires new users to change their approach to CAD:

> "[Cloud-CAD] made me think differently about how to design multiple components that were all going to fit or work together somehow. I think my design and development process was really efficient because you could really edit everything at the same time." (P12)

Rather than feeling limited into one structure, users have described Onshape as "very flexible in how you can use it" (P9).

4.5 Intermediate Check-ins

The nature of cloud-CAD facilitates document sharing. Rather than waiting for formal opportunities for design reviews, participants found that they became familiar with each other's designs during the modelling process. Participants described the virtual interface mimicking that of a physical environment:

> "The real key is that I can see [their work] in real-time, so I don't need [my coworkers] to check-in [a model]. I can just go poke around and see what they're doing, in the same way if we were working in the machine shop on something, I can look over their shoulder, see what they're working on, and see if [the work] is relevant to me." (P8)

With the ease of looking at others' projects, this same interviewee recalled how they encountered impromptu mini-design reviews during the modelling stage, resulting in the formal reviews lasting fifteen minutes instead of the usual two hours. Able to navigate easily through the project, the entire team familiarized themselves with the components, allowing feedback to be incorporated gradually throughout the entire design process rather than all at once.

The ability to observe another project also provided learning opportunities. P6 described cloud-CAD as a good learning environment because it was "a place to exchange ideas and see how people CAD." By observing other teammates do CAD in real-time, they were able to learn good practices. This sharing extends beyond engineers, as even those who are not designers can provide their input on the model. Another participant (P2) mentioned how cloud-CAD allowed individuals from different backgrounds to collaborate because the software has a lower entry barrier: "Each person on the team had fairly different skillsets. . . [and] we were able to have very productive conversations because we knew what we were working on." With link sharing, coordination between departments becomes simpler.

5. Discussion and Implications for Teaching

Next, we will review the themes and define relationships between them based on the contexts in which the themes will be most relevant/impactful to the software adoption process: pre-, peri-, and post-adoption. We will further share recommendations for teaching cloud-CAD to facilitate activity during each stage.

In the pre-adoption phase, we identified themes prominent during the initial onboarding of the software: *Individual's Aversion to Change*, *Right Tool for the Organization*, *Underutilized Features*. Therefore, CAD users should familiarize themselves with the capabilities and strategies of cloud-CAD to minimize uncertainties during uptake. While in the early stages of adoption, advanced collaboration and team data management features are not crucial to the process, but if implemented, they can create a foundation for the company's cloud-CAD use as the team begins to expand.

The peri-adoption phase relates to when the organization fully integrates the software into their daily practices; this phase encapsulates *Right Tool for the Organization*, *Underutilized Features*, and *Implicit Coordination via Workflow Features*. With more control over their workflow, engineers can use the different tools that the software offers to create a methodology that best fits their needs. By learning standard workflow processes, they can smoothly transition from traditional to cloud-CAD because they know practices applicable in both environments.

The post-adoption phase consists of *Implicit Coordination via Workflow Features* and *Intermediate Check-ins*; these themes focus on how individuals collaborate in practice. Introducing spontaneous check-ins encourages CAD users to seek feedback to improve their designs and provide equally beneficial critiques to their peers. To create such an environment, we need to emphasize psychological safety in cloud-CAD, allowing designers to experiment on models without fear of scrutiny.

Reflecting on our learning from industry designers and their use of cloud-CAD, we next draw conclusions to inform the teaching of CAD to student designers. To ensure students are prepared to excel in their future design work, we provide the following recommendations to teaching cloud-CAD: "Introduce Alternative CAD Styles to Allow for Flexibility," "Establish Standard Workflows to Facilitate Coordination," and "Foster an Environment for Psychological Safety". In Fig. 4, we display the breakdown of relevant context for each theme, followed by our recommendations to ensure the themes are properly incorporated as lessons in CAD instruction. In the next sections we elaborate on these recommendations.

5.1 Introduce Alternative CAD Styles to Allow for Flexibility

In pre-adoption, the primary concern engineers have is whether learning cloud-CAD is a necessity. Most engineers in our study were familiar with the traditional software SolidWorks before adopting Onshape, and they expressed their initial reservations about learning the emerging software. Inhibitions were primarily a result of unfamiliarity and a perceived lack of need. Since traditional CAD has been used for many years and is seen as the industry standard, the switching cost remains high. It is likely that by exposing students to the potential benefits of cloud-CAD, they will be more open to this form of software, especially as the shift to remote work becomes more pronounced.

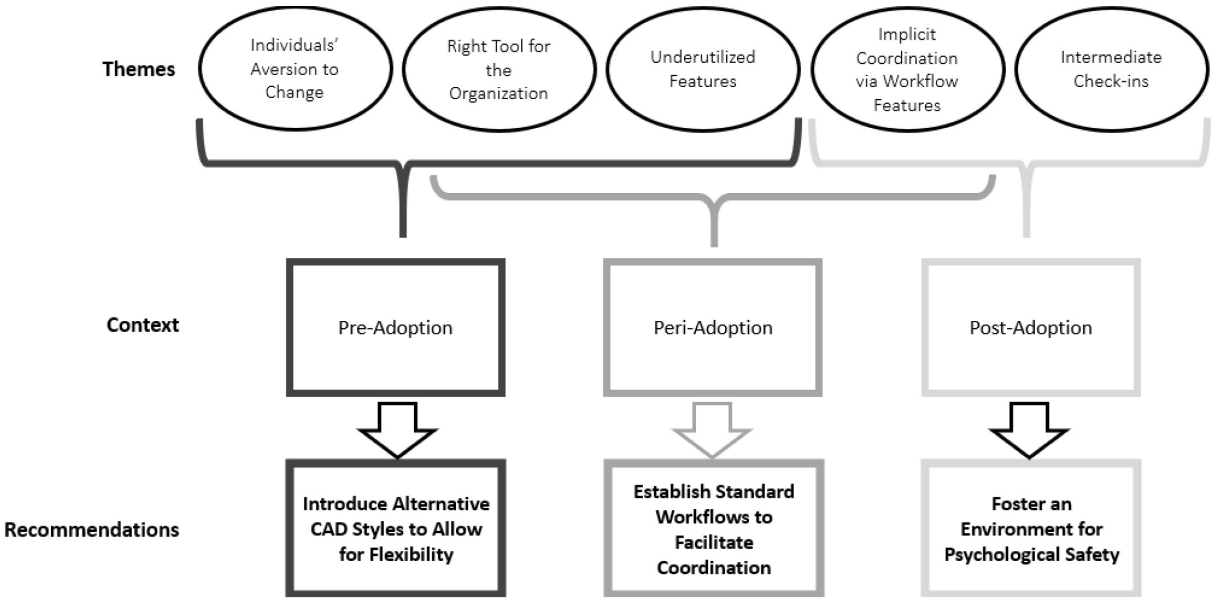

Fig. 4. The breakdown of themes into their appropriate contexts, along with the corresponding recommendations to best address the themes in an educational setting.

Our study found that the younger participants were more accustomed to cloud-CAD because they encountered it early on in their training and developed their CAD style in conjunction with the software. In doing so, designers can fully explore the software's capabilities and determine which tools best benefit their workflow. While cloud-CAD may not currently be an industry standard, an early introduction will help designers navigate through either traditional or cloud-CAD depending on which best meets their needs and the needs of their organization.

Many of the new features introduced in cloud-CAD are already being widely used in other fields like computer programming. Notably, the collaborative aspect of CAD is similar to that of GitHub. Studies have explored the introduction of GitHub as a teaching tool [32, 40]. Students learned collaborative skills and effective coding strategies and believed these skills could be applied to their careers later on [33]. Similarly, the introduction of cloud-CAD at the university level can allow students to not only develop their CAD prowess but also improve their collaborative skills and communication.

To introduce alternate CAD styles when teaching CAD, we recommend offering opportunities to learn both traditional and cloud software. This approach involves moving away from exclusively teaching declarative knowledge via drafting exercises and including more procedural knowledge at the level of the full design workflow, such that students can appreciate the strengths and weaknesses of different CAD styles.

5.2 Establish Standard Workflows to Facilitate Coordination

Not all teams can use cloud-CAD to its full capabilities either due to a project's needs or the company's size. For this reason, it is crucial to introduce workflows in the curriculum that cloud-CAD can help foster. In peri-adoption, the designers acclimate to the new software and begin actively using it for their projects. While we previously focused on engineers learning the fundamentals, now we emphasize teaching strategy and effective work habits.

Standardization creates a baseline understanding of how a team functions, making it easier for designers to learn the work process and produce a consistent quality of work [41]. Although there are few common, standardized approaches to cloud-CAD, through our interviews we discovered a number of promising strategies that we believe can effectively impact a company's workflow. As previously discussed, versions and releases can both be used to indicate and coordinate project progression and milestones, with the latter requiring formal approval. These subtleties create an implicit language facilitating communication. Additionally, other strategies can help with navigating through a project. For example, top-down design, an approach in which few parameters control numerous parts, becomes more pivotal in cloud-CAD than in traditional CAD. Seeing part interactions allows designers to understand exactly how parts are related and how changes in one area may impact another. Introducing these practices into the CAD curriculum requires students to think about the impact their contributions have on the entire project.

The type of environment that newly graduated designers will enter will require different strategies depending on where the company is in its lifecycle [42]. The flexibility of cloud-CAD means it can accommodate various design workflows. Having been taught numerous standardized strategies, engineers can use their judgement to determine which approaches best meet a company's needs. Furthermore, having workers well-versed in various CAD strategies permits a company to easily transition from a more organic system to a more organized one.

To teach these strategies in a course setting, we recommend the instruction move beyond simply modelling and include effective use of workflow management features. When assigning projects, educators should emphasize the importance of properly using versions and releases. To enforce this approach, we suggest adding criteria to projects that not only focus on the quality of the final product but also on how well designers have documented their process. Furthermore, the inclusion of an open-ended, creativity-driven project would provide the opportunity for students to explore branches in their workflows. At each stage, students could design alternatives in branches; these branches serve as experimental grounds, and students can use this area to explore the different approaches in completing their project. Upon meeting the appropriate criteria and receiving approval, they can merge their work into the main branch.

5.3 Foster an Environment for Psychological Safety

We next emphasize the ability to collaborate effectively, which is essential for the post-adoption phase. Cloud-CAD can help foster team dynamics in new ways by creating a psychologically safe team environment. Psychological safety is defined as a teammate feeling the security to take interpersonal risks in the workplace without the fear of negative consequences [43]. In psychologically safe areas, ideas are shared more freely because there is little fear of scrutiny [44]. By creating an environment that enables transparency and collaboration, and thus interpersonal risk-taking, teammates may be more willing to point out mistakes, provide constructive feedback, and experiment with highly creative ideas.

Since Onshape retains all changes, individual contributors do not have to worry about ''breaking'' a model; edits can be reversed at any point. Branches also offer the opportunity for experimental changes; designers can test their models in these areas without directly impacting the main workspace. The use of these features creates fail-safes in project development.

With the project readily available on the cloud, documents become accessible at any point in the project lifecycle. When documents are shared, designers are assured that they are viewing the most updated models. With traditional CAD, after a version is shared, updates made to the original model are not backpropagated, resulting in a loss of control if the original model and shared version develop into separate entities.

Link-sharing, therefore, becomes the key to transparency in cloud-CAD. The barrier of communication decreases as individuals can access a project at any point along its development lifecycle. Transparency becomes the biggest contributor to psychological safety. Working in such an exposed environment requires vulnerability because designers lose control over when their work becomes visible to their teammates. Designers must be prepared to defend and explain their contributions at any point in the design process.

Being exposed to peer reviews is imperative to engineering undergraduate students. By learning to self-review and take constructive feedback from their peers, students can evolve and improve their designs rather than be fixated on their original idea. Along with the need for vulnerability comes a need for trust and respect. Link-sharing introduces the risk of surveillance. Having the ability to view their teammates' works requires individuals to be responsible and mindful of how and when they choose to access these documents, and how they deliver critique to their peers. Cloud-CAD implementation at the educational level introduces students to these phenomena early on and provides them with the environment to learn respectful habits. By creating a virtual workplace that mimics a physical one, individuals are not only encouraged to engage in peer reviews but also to take a critical look at their own work. Creating online environments that promote cooperation and growth creates a space that nurtures psychological safety [45].

We recommend beginning to create these positive team environments by integrating peer reviews into the design process in the classroom. By requiring students to critically analyze their teammates' work, educators teach the importance of collaborating and providing constructive feedback. Overall, students can be evaluated on their design outcomes, the quality of reflections regarding the culture their team has established, and whether they are collaborating in a psychologically safe manner.

6. Conclusion and Future Work

6.1 Conclusion

CAD is an essential tool that has helped engineers design for years, however, many of its features have remained static for some time. But with the technology-driven change in engineering work, CAD is changing too, in the form of cloud-CAD. With cloud-CAD, teammates have easy access to each other's models, advanced versioning features, and novel collaboration capabilities. The current CAD curriculum should be updated to address these changes, strengthening student designers' abilities to not only CAD but design as a whole.

From the conducted interviews, we identified three critical concepts to incorporate into the ways we teach CAD:

1. Introduce Alternative CAD Styles to Allow for Flexibility.
2. Establish Standard Workflows to Facilitate Coordination.
3. Foster an Environment for Psychological Safety.

By adopting these concepts in our teaching, we can influence how up-and-coming engineers approach design and collaborate with one another. Traditional CAD was an individual task, which over time has influenced how the teaching curriculum has developed. As the uptake of cloud-CAD continues to grow, so too must the education system to meet the new demands.

6.2 Limitations and Future Work

We should be conscious of our limited participant pool that was predominantly male and White. Given the research indicating that gender is a crucial lens through which to consider spatial reasoning tasks, the study would benefit from having a more diverse pool to better represent the student population that we aim to support. Further, most of the represented companies identified as startups or recently adopted the software; however, our analyses would benefit from seeking representation from larger established companies using cloud-CAD. Finally, our conclusions are made using grounded theory, which limits the claims of our results to our participant pool. This research sets the foundation for potential experiments to verify whether the claims hold in the general population.

This research proposes theories on how teaching CAD can be influenced by cloud-CAD. The suggestions provide a foundation of theories that can each be tackled in follow-on studies. One study of interest would seek to better understand how cloud-CAD can create a psychologically safe environment, and therefore more effective and innovative teams.

Additionally, one cloud-specific feature that could aid future experiments is analytics, which documents user activity. As previously discussed, our Onshape Enterprise participants focused predominantly on the simple analytic of CAD hours logged. There is opportunity to study which analytics would best inform designer-improvement and reflection, and to exploit these analytics for the purpose of better understanding cloud-CAD behaviours.

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Appendix – Interview Guide

Introduction

1. To start off, I am going ask you a few questions about *company* and your role in the company.
    (a) How long have you been working with your company?
    (b) What's the size of your company?
    (c) What type of products do you work on?
2. Can you please describe your team's work and your role within the team?
    (a) What is the size of your team?
    (b) What are your typical responsibilities?
    (c) How much of your job is CAD?
    (d) How much of your organization uses Onshape?
3. How often do you collaborate with teammates that are overseas or in different time zones?

Learning Onshape

Now we are going to focus on your experience with learning to use Onshape.

1. Before that, however, can you explain your experience with CAD or modelling software in general?
2. Was Onshape something you were familiar with beforehand or did you learn it for *company*.
3. Can you explain your process of getting used to Onshape?
    (a) Did you take any online classes?
    (b) Did your company provide any learning resources?
    (c) In retrospect, what would have been helpful to better learning?
    (d) How long did it take you to feel confident?
4. What features were easier to pick up in Onshape?
5. What features were more difficult to pick up in Onshape?
6. Were there any missing features in Onshape that you found useful/helpful in other software you used?
    (a) What were these features?
    (b) How did you get around these?

Using Onshape: Communication and Data Management

Now we will be focusing on how you use Onshape during your normal work operations.

1. Onshape has a collaborative environment similar to that of Google Docs. Can you explain your process of collaborating with others when modelling?
    (a) Are you ever actively collaborating with another designer in the same document at the same time?
    (b) Do you collaborate with team members? Do you collaborate with stakeholders upstream (marketing) or downstream (manufacturing) from your role?
2. Onshape makes use of different features such as branches, versions, and releases. Do you use these features?
3. Can you walk us through an example project and discuss how you make use of any of these features?
4. How does your team go about managing different iterations of a model?
5. How does your team make use of versions?
    (a) When are they made?
    (b) How often do people refer back to versions?
6. How does your team go about updating the "ground truth" model?
    (c) Who has final say in who updates the final model?
7. Does your team make use of releases?
    (a) When does a release get made?
    (b) What are the reactions to releases being approved/rejected?
    (c) If they are rejected, who becomes responsible for fixing it?
8. How do you communicate changes to your teammates?
9. What are common challenges with communicating with members that are overseas?
    (a) Has Onshape helped facilitate these difficulties? If so, how?
10. Are you familiar with Onshape Analytics?
    (a) Have you ever looked at them? If so, what do they tell you about your team?
    (b) Have there ever been any changes in response to the analytics? If so can you provide an example?

General

1. Do you think the use of Onshape as a tool has changed your CAD style? How?
2. Do you think the use of Onshape as a tool has changed your team's CAD style? How?
3. What are the biggest barriers in Onshape that currently hold you back?

Follow-up

1. Is there anything we haven't asked about working with Onshape that you think we should know?

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