In the Age of Collaboration, the Computer-Aided Design Ecosystem is Behind: An Interview Study of Distributed CAD Practice

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Computer-aided design (CAD) has become indispensable to increasingly collaborative hardware design processes. Despite the long-standing and growing need for collaboration with CAD models and tools, anecdotal reports and ongoing researcher efforts point to a complex and unresolved set of challenges faced by designers when working with distributed CAD. We aim to close this academic-practitioner knowledge gap through the first systematic study of professional user-driven CAD collaboration challenges. In this work, we conduct semi-structured interviews with 20 CAD professionals of diverse industries, roles, and experience levels to understand their collaborative workflows with distributed CAD tools. In total, we identify 14 challenges related to collaborative design, communication, data management, and permissioning that are currently impeding effective collaboration in professional CAD teams. Our systematic classification of CAD collaboration challenges presents a guide for pressing areas of future work, highlighting important implications for CAD researchers, practitioners, and tool builders to target new advancement in CAD infrastructure, management choices, and modelling best practices. With the insights gained from this work, we hope to ultimately improve collaboration efficiency, quality, and innovation for future product design teams.

CCS Concepts: • **Human-centered computing** → **Empirical studies in collaborative and social computing**; • **Applied computing** → **Computer-aided design**.

Additional Key Words and Phrases: Computer-Aided Design, Product Design and Development, Collaborative Design, Collaboration Challenges

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1 INTRODUCTION

Effective and efficient collaboration is an important prerequisite for successful product development projects in engineering. Collaborative design can leverage the individual capabilities of engineers to create superior quality and cutting-edge products faster than ever before [77]. During the last few decades, design practices have been transformed by globalization and computerization, making

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collaboration possible for engineers separated by disciplines, companies, and even countries [21]. As engineering projects become increasingly distributed and globalized, it is imperative to optimize collaborative workflows in product development.

Computer-aided design (CAD) is an essential digital tool used within collaborative workflows for product development, allowing engineers to virtually design and test product concepts before physical fabrication [7, 92, 100]. Many types of CAD exist to support engineers of all disciplines, but our work focuses on mechanical CAD, used principally by mechanical engineers in the design of practically all modern human-made physical products. Despite the importance and widespread use of CAD in product development [44], designers continue to report challenges with collaboration, and there is not yet a unified solution that addresses this complex workflow [39]. Researchers have attempted to resolve some previously identified challenges of collaboration, such as conflict management during concurrent design [49, 76] and inconsistent design practices between designers [9, 86]. Yet anecdotal evidence suggests that these, and other collaboration challenges such as lack of support for offline editing [68], difficulty sharing CAD files [12], complexity of CAD data management software [13], lack of support for cloud collaboration [68], and non-interoperability between CAD platforms [102, 105] impede the computer-supported cooperative work of CAD.

Since the creation of CAD, three generations of CAD tools have emerged — standalone, distributed, and collaborative — which can be classified using the computer-supported cooperative work (CSCW) time and place matrix [66, 107]. *Standalone CAD* (also known as single-user CAD) is used by an individual designer on a local computer system (same-place, same-time). When standalone CAD is combined with a data management system that enables geographically distributed or co-located designers to access shared files, this is considered *distributed CAD* (different-place or same-place, different-time) [47]. In recent years, *collaborative CAD* (also known as synchronous multi-user CAD [MUCAD]) has begun to attract attention from researchers and CAD companies alike, whereby multiple designers are able to contribute to the same CAD file synchronously (different-place, same-time) [33, 47, 73, 79, 110]. In these studies, it has been suggested that MUCAD software can resolve some common collaboration pain points (e.g., incapability of synchronous editing, seamless file-sharing, and visibility of design changes).

However, in practice, the transition from distributed CAD to collaborative CAD is slow, and few product design companies use this new generation tool. In fact, as of 2017, less than 10% of professional design enterprises globally have implemented cloud-based CAD, and over 50% of enterprises are not considering implementing cloud-based CAD at all [65]. A newer study from 2021 found that the adoption of cloud-based CAD grew to 50% for hobbyists but only to 20% for professionals [104]. This slow shift may be due to the centrality of CAD to the development process at these firms, creating a dependence on the current status-quo and reluctance for change; it could further be motivated by skepticism towards cloud tools, and poor understanding of the benefits [65]. As such, although collaborative tools are emerging, they currently hold a small portion of the market, and due to entrenched processes, we expect that they will not take over distributed CAD in the short- or medium-term. We aim to present a systematic perspective on collaboration based on current design practices, and thus we chose to exclusively focuses our work on the experiences of the majority of practitioners – those who use distributed CAD.

Our goal is to close the knowledge gap of CAD collaboration challenges that exist between researchers and practitioners through investigating current practices of CAD designers, challenges in the CAD workflow, and strategies that may resolve common collaboration challenges. We conduct semi-structured interviews with 20 CAD professionals to answer the following research questions:

RQ1: What are the collaboration challenges faced by professionals using distributed CAD?

RQ2: What strategies are CAD professionals or organizations using to remedy collaboration challenges with distributed CAD?

Similar industry-driven systematic studies have recently made important contributions in other CSCW fields, including computational notebooks [17], AI-based software development [71], referencing patterns in pull requests [23], and fairness assessment in machine learning [53].

Our work makes the following contributions to the CSCW community:

(1) Empirical findings from 20 interviews, showing that CAD designers encounter collaboration challenges within many key aspects of the product development process – including collaborative design, synchronous communication, data management, and file permissioning. While some of our interviewees have developed workarounds to alleviate challenges, they also disclose that these workarounds lack formalization, bring pain points of their own, and are presently incapable of addressing all collaboration challenges.
(2) Several previously unreported CAD collaboration challenges to motivate future work in improving CAD groupware, such as poor traceability of CAD designs caused by scattered file management, difficulty presenting live CAD models in design reviews, and lack of change summarization documentation due to lack of tooling support.
(3) Targeted proposed solutions for CAD tooling support, better management, and best practices to address the 14 collaboration challenges presented in this work.

2 BACKGROUND & RELATED WORK

2.1 Background of CAD Collaboration

2.1.1 Distributed CAD. CAD systems can be standalone (similar to same-place, same-time, but in this case, one person at-a-time), distributed (different-place or same-place, different-time), or collaborative (different-place, same-time or different-time) [66, 107]. Distributed CAD is characterized as a CAD tool used in combination with a data management system that facilitates the transfer, storage, and management of CAD files such that they can be accessed by several geographically distributed or co-located users [47]. Like distributed CAD, collaborative CAD also supports multiple users and enables the users to interact; however, collaborative CAD additionally supports synchronicity, which allows users to view, edit, and manipulate a model that updates for each user in real-time. Thus, the key difference between distributed CAD and collaborative CAD is the multi-user synchronous working environment [50].

Given that the focus of our study, distributed CAD, by definition, requires a data management tool to supplement the CAD tool itself, we find it relevant to provide a background on the types of data management tools used in the distributed CAD ecosystem. Data management for CAD can be *manual*, *partially-automated*, and *fully-automated* [93]. An example of manual data management is Dropbox, which stores CAD files and automatically creates backups of uploaded files, but does not support any sophisticated features for CAD version control (e.g., the ability to control which users have the authority to set revisions, the ability to publish released designs to stakeholders, to indicate that a version is a revision). Partially-automated data management offers additional functionalities such as tracking each time a user checks in a new version of a file, allowing files to be restored to a previous version, and designating a version as a revision. Fully-automated data management (i.e., Product Lifecycle Management [PLM] and Product Data Management [PDM]) takes this a step further in its ability to be highly customizable to satisfy the needs of any organization — particularly larger companies that have ample resources to afford and maintain it. PLM systems can be configured to track modifications to CAD data, manage product evolution, provide workflows to route files to specific people (e.g. for design approvals), and enable specific permissions for different users [11].

While distributed CAD is widely used in professional design practice, CAD professionals continue to report collaboration challenges that hinder effective product development. Thus, a systematic study is needed to better understand the challenges CAD designers face and methods to address these issues.

2.1.2 CAD Collaboration Challenges. Although there is a lack of empirical, systematic studies focused on CAD collaboration challenges, a number of pain points have been documented in the existing literature. Here, we piece together these previously identified challenges to provide an overview of the current landscape of CAD collaboration research. One of the most discussed challenges is inconsistency in design practices between designers. Every designer generally has their own unique way of modelling in CAD, but this poses a challenge to collaboration when models created by one designer cannot be easily understood, altered, or reused by others [9, 86]. Since variability in CAD modelling is a source of frustration for many designers, some best practices for modelling have been published to help standardize and optimize modelling techniques [54, 69]. Many researchers have also discussed the non-interoperability of CAD files as a barrier to collaboration, making it difficult for models created in one CAD system to be reliably translated and transferred to another [56]. Sharing CAD files is a fundamental aspect of CAD collaboration, and when designers use different CAD platforms, CAD files must be converted into a neutral file format, or *dumb solid* (e.g., STEP [Standard for the Exchange of Product Data]), interoperable between different platforms [20].

Regarding data management, the version control of CAD files has long been a challenge in the CAD community [11, 39, 81]. Although tasks like managing parallel versions, keeping designs up to date, and synchronizing CAD files between designers can now be fully-automated with PLM systems, other aspects of CAD data management remain a challenge – for example, managing CAD files and related documentation in a way that maintains traceability of the design process [56] and of linked CAD files [39].

While the collaboration challenges discussed above are universal among most teams, collaboration can be more complicated for distributed and multidisciplinary teams [21]. Previous studies investigating practices in *distributed product design teams* found that language, time zones and cultural barriers can exacerbate collaboration challenges in co-located design teams – for example, greater misunderstandings of design intent and inefficient communication and propagation of design changes [40, 64]. Kuenzel et al. observed workflows in *cross-company collaboration* which face the unique challenges of intellectual property (IP) issues, changes to management structure and distribution of labour, and technical issues with data exchange [58]. Thus, to support increasingly common cross-company collaboration, organizations must prioritize the integration and enforcement of standards, IT coordination, and data and knowledge management [63]. Hollander et al. studied product development in *multidisciplinary teams*, specifically designing electromechanical products, whereby collaborating mechanical and electrical engineers must navigate the nuances of each discipline's respective standards, best practices, jargon, and schemata (way of understanding and solving a problem) [52].

Collectively, previous research has provided important insights into some well-known collaboration pain points in CAD practice. However, the existing body of literature lacks systematic studies, and few take an empirical approach with real CAD practitioners to address this gap. To the best of our knowledge, our work is the first to systematically identify and develop a framework to classify collaboration challenges with distributed CAD.

2.2 Related Work in Collaborative Software Development

Similar to CAD design, software development procedure is inherently collaborative, requiring software engineers to coordinate their efforts to produce a software system. Software teams could be co-located or distributed, and collaborate synchronously or asynchronously. While global software development is becoming a way of life, such work takes much longer than co-located work [51], and suffers from a wide range of problems, such as a lack of group awareness, inefficient communication, and more management overhead [55, 74]. Recent advances in distributed version control and the branching and merging mechanism (e.g., Git) [1] facilitates collaboration in distributed software teams, as developers are able to work on their own code base asynchronously without affecting each other. However, there are still challenges within distributed and asynchronous settings. When the number of team members grows, it becomes difficult to maintain an overview of what happens in individual workspaces [16, 28]. Researchers have studied different types of awareness for collaborative work [35] and designed tools to summarize the activities among the team members to raise the awareness during the collaboration procedure [27, 35, 46, 89, 90, 101, 111].

Like collaborative software development, collaborative CAD design suffers from collaborative distance, overhead of synchronization, and management. Prior work in the software engineering research domain presented tools and methods to support better traceability of the related artifacts and help stakeholders maintain a better overview and manage scattered documentation throughout the software development lifecycle [5, 59, 78, 83]. During the implementation stage, developers are mainly writing code using an integrated development environment (IDE) that provides comprehensive facilities such as source code editor and debugger. Additionally, the version control system can easily highlight the code changes between two versions, identify text-based merge conflicts, and support asynchronous collaboration smoothly. However, in comparison to the implementation phase in software development, hardware designers work on CAD models, which represent complex geometric and topological data [39] and are different from the text-based source code generated in the software development procedure.

Therefore, while lessons from software development collaboration are informative to CAD researchers and users, the difference in development motivates a dedicated study. The present study aims to address the lack of empirical investigations to guide future research, as well as tool selection and tool design to best support CAD collaboration.

3 METHODS

In this study, we conducted semi-structured interviews with CAD professionals. Semi-structured interviews are appropriate for our study due to the lack of existing research on CAD collaboration challenges as well as the exploratory nature of our research questions [96]. Since our aim is to investigate the collaboration challenges faced by CAD professionals, interviews were the ideal way to gather authentic experiences. We continued interviewing until each additional interviewee introduced no new challenges of any kind, indicating theoretical saturation. The study was approved by the University of Toronto Ethics Review Office.

3.1 Recruitment

We employed a combination of snowball and voluntary response sampling methods, which are both appropriate for qualitative data collection [42, 70]. Interviewees were recruited through our personal and professional networks, as well as through advertisements posted in CAD-related LinkedIn groups. The interviews were conducted by a combination of the first three authors, with the majority of interviews led by the first author.

3.2 Participants

In total, we interviewed 20 CAD practitioners, all of whom use CAD to fulfill their primary job responsibilities. Five interviewees were women (25%) and 15 were men (75%). Our interviewee pool ranged in seniority and included mechanical engineering interns, junior and senior engineers, team leads and a CEO. The average length of experience working with CAD professionally is 7.8 years (*sd* = 6.8), which can be considered well into the range of senior engineer [37]. Within our sample, five interviewees (25%) work in the aerospace industry, four interviewees (20%) work in the automotive industry, and four interviewees (20%) work in the electronics industry. Regarding CAD software tools, interviewees primarily reported using NX (35%), SolidWorks (35%), CATIA (25%) and Creo (25%); 50% of interviewees use two or more CAD software on a regular basis. Four interviewees use manual version control and 16 use fully-automated PLM tools; of the four manual users, three work in small companies (<100 employees), and 15 of 16 PLM users work in large companies (>500 employees). Figure 1 in Appendix A summarizes the interviewee information.

In the following paragraphs, we discuss the descriptive characteristics of our participant pool with regards to CAD collaboration and CAD knowledge. This data was collected in a follow-up survey that was sent to participants six to eight months after the interview, and 17 of the original 20 interviewees responded. We were unable to gather such information from three interviewees.

Collaboration Characteristics. In terms of collaboration, 15 of the 17 interviewees who responded to our follow-up survey work on multiple design projects simultaneously: the range spans from one interviewee working on one project at a time (ID1 and ID17) and the most being up to 10 simultaneous design projects (ID9). All 20 interviewees collaborate with other designers who interact with the CAD models on a regular basis, with the majority of interviewees having around up to 10 collaborators, though ID13 (aerospace industry) reported collaborating with 50 other designers. When it comes to collaborating with an external organization (e.g., a client, supplier, other design firm), all 17 interviewees have some such responsibility, with the percentage of time spent collaborating externally ranging from 10-40% for regular design work, to 90% for some designers (ID4 and ID17) specifically during design review meetings. Regarding synchronous work settings like design reviews, all 17 interviewees report that they spent a portion of their time working synchronously with other collaborators, with 5% being the least amount of time working synchronously (ID11, ID13, ID15, ID19) and 75% being the largest percentage of time spent for synchronous work (ID4). In summary, all designers must collaborate both internally and externally, and it is common practice to work on multiple simultaneous projects as well as in synchronous work settings.

CAD Knowledge Characteristics. As CAD software is continually improving, it is important to ask participants how often they update their knowledge and awareness of new CAD tools and features to ensure that the collaboration challenges mentioned are relevant to the current landscape of CAD collaboration. Of the 17 interviewees, five update their CAD knowledge regularly (a few times a month), nine update their knowledge occasionally (a few times a year), and three interviewees rarely update their CAD knowledge (once a year or fewer). When the interviewees do update their CAD knowledge, eight learn from colleagues, eight from online CAD forums and blogposts, six from company newsletters or internal training, five from online tutorials, three from a technical trainer from a CAD vendor, and one from reading CAD software user manuals. Overall, the majority of participants (14 of 17) actively update their knowledge of current CAD technology and designers most often seek help from colleagues, online forums, and internal training.

These characteristics show that our participants are experienced in CAD collaboration and knowledgeable about modern CAD tools, and therefore are well-suited to shed light on CAD collaboration challenges.

3.3 Interview Protocol

Our interview protocol focused on gaining a thorough understanding of the design process within each interviewee's team, with an emphasis on instances during the design process that involve collaboration with CAD. We designed the interview with simple prompt questions for interviewees to reflect on and recall difficult, frustrating, inefficient, or time-consuming tasks. When interviewees brought up challenges organically, we prompted further detailed discussion on the causes of these challenges, along with strategies implemented by the individual or the organization to overcome identified challenges. The interview script roughly followed the five prompts:

- Describe their job role, academic and professional background, and professional experience with CAD.
- Describe their typical project and CAD design process, specifically focused on instances where CAD is used collaboratively.
- Recount issues, slowdowns, and pain points within their CAD collaboration process.
- Describe tools, processes, and other strategies that help to alleviate and/or mitigate pain points.
- Provide a comprehensive list of the tools that are involved in their CAD workflow, which may include CAD programs, PLM/PDM or version control systems, and/or simulation software.

3.4 Logistics

Prior to participating in interviews, interviewees signed an informed consent form. No compensation was provided, and participation was voluntary. The duration of each interview was between 35 and 80 minutes, with the average interview lasting 55 minutes. All 20 interviews were conducted via Zoom videoconferencing software and were audio-recorded and automatically transcribed using Zoom's transcription service.

3.5 Data Analysis

Interview transcripts were anonymized and imported into NVivo qualitative research software[1]. To begin analysis, the first three authors collaboratively analyzed the transcripts with an open coding process [88]. We took an inductive approach because there are no widely accepted categorizations for CAD collaboration challenges. Participant statements that described the same topic were gathered into codes, which we labelled with short descriptive phrases to summarize the aspect of the CAD process. As interviewees mentioned additional challenges and strategies, the codes were expanded to reflect the new information. In total three rounds of coding were performed. In the first coding round, participant quotes were coded to specific activities in the CAD design process, which resulted in 11 different activities: *working with old files, editing models created by other designers, accessing shared files, concurrent modelling, coordinating files between multiple projects, modelling interacting parts or sub-assemblies, managing file versions, communication about CAD or design intent, synchronous editing, releasing model updates/changes, collaborating with external organizations,* and *collaborating with other teams within the same organization.*

In the second round of coding, we coded specific challenges and strategies within each activity. Challenges were identified as the underlying cause of why a particular task is inefficient or frustrating, and strategies were identified as any tool, measure or workaround used to alleviate a challenge.

[1]https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

In the third and last round, axial coding was performed in order to group similar challenges and draw relationships between them to identify higher-level themes. This process involved iteration between interview data and additional literature searches to confirm relationships between challenges and strategies, which is characteristic of qualitative research analysis [24]. In the end, our coding revealed four key themes: collaborative design, synchronous communication, data management, and permissioning. Challenges and strategies in these four categories are discussed in the next section of this paper.

4 RESULTS

In this section, we report on the various collaboration challenges and corresponding strategies identified through the 20 interviews. Although our interviewee pool represents CAD practitioners from diverse industries, roles, and experience levels, we observed commonalities among types of CAD collaboration challenges and the workarounds/strategies that help alleviate challenges. From our 20 interviews, a total of 14 challenges and seven strategies were found. It should be noted that not all challenges were matched with a participant-described strategy, but each strategy addresses a specific challenge. To present our results, we divide the challenges and strategies into four categories: (1) collaborative design, (2) synchronous communication, (3) data management, and (4) permissioning. Challenges within each category are sorted by how pervasive they were amongst our participants.

4.1 Collaborative Design Challenges and Strategies

This section discusses challenges that occur when multiple designers must coordinate and work together to perform design activities with CAD models. If left unresolved, challenges with collaborative design can result in designers making conflicting edits, overwriting each other's work, or creating duplicate work, overall decreasing the working efficiency. Collaborative design challenges were discussed in all 20 interviews, revealing a total of five challenges and two strategies.

Challenge 1: Absent or varied modelling conventions across collaborators

Of our 20 interviewees, 10 indicated that collaborating designers frequently follow different modelling conventions. One example is when designers use varied part orientations and coordinate systems in their CAD models. In CAD, coordinate systems are used to define points relative to the object being modeled which can assist in the assembly process. In the ideal situation, explained by ID2, *"if you drop all [the parts] into the same assembly file, you can just line up all their coordinates together and the model should basically assemble itself and everything should be in the right place."* When designers follow different conventions for defining coordinates, it can be frustrating and time-consuming to assemble all of the components manually (ID2, ID11, ID14, ID17).

Varied conventions are also common in cross-company collaboration, where teams in different organizations set different standards for design tolerancing (ID18), or in multidisciplinary teams, where mechanical CAD models interface with electrical engineering (EE) CAD models. This can be challenging because mechanical and electrical engineers follow different conventions (ID9, ID10). As one interviewee points out, electrical engineers use maximum dimensional size while mechanical engineers use nominal size; these slight differences can create conflicts when mechanical and EE CAD parts interface (ID18). These nuances can complicate communication, and as a result, hinder interdisciplinary collaboration.

Collaborative design can additionally be challenging if designers fail to follow standards. In a CAD context, a designer may neglect modelling best practices, proper referencing, commenting, and/or documentation. Consequently, other designers who may need to later edit the model may have difficulty understanding how the model was made and how to appropriately make changes. In the worst-case scenario, the new designer will need to completely recreate the model from scratch, which could take hours or even days, depending on the complexity of the model (ID1, ID2, ID5, ID9, ID10, ID13, ID18). In industries where new products are risky, complex, and often derivative of older products, designers tend to avoid starting a model from scratch, preferring to create a copy of a previous model and make modifications (ID8, ID9). In these instances, it is therefore especially important to establish and follow unified modelling conventions.

Strategy 1: Imposing standards and best practices for modelling. As discussed with reference to the challenges above, it is possible to alleviate some of the challenges of varied modelling practices via best practices and conventions. Therefore, a rather obvious strategy to address these challenges is to encourage, expand and enforce those best practices that exist. Indeed, our interviewees argued that unified best practices should be enforced to standardize each designer's modelling method and reduce rework (ID1, ID4, ID10). Yet, many interviewees state that it can be difficult and complex to successfully enforce modelling standards (ID1, ID13, ID14, ID17). However, ID10, an interviewee who started their own design company, was able to accomplish standardizing the modelling procedure. As ID10 explained, "*we made two documents for standardizing the procedure and then we gave it to all new designers who are coming into the company. It cannot happen overnight – it took two to three years until all our designers got trained on the modelling procedure and then it was OK. It took three years to [bear] fruits, but afterwards everybody was modelling in the same way.*" While standardizing modelling practices within a single company may be achievable, standardizing practices cross-company is even more complex and challenging. Thus, varied modelling conventions between companies will likely remain a challenge.

Challenge 2: Infrequent model uploads prevent contribution from collaborators

When using *distributed* CAD, team members are collaboratively but asynchronously working on a centralized database. A designer "checks out"[2] a CAD model to their local workstation and later integrates the changes back to the shared repository. With this workflow, design progress can be impeded if designers upload models infrequently (ID2, ID15), or forget to check models in after editing, effectively preventing others from being able to work on the file (ID1, ID3, ID6, ID7, ID8, ID10, ID11, ID12, ID16, ID19). As put by ID1, *"it can seem trivial, but when there's 1000 parts in an assembly, it makes it a big challenge to make sure that the right parts are checked in."*

Challenge 3: Lack of designer awareness of model dependencies

When starting a new project, designers will sometimes start from an old model from a previous project. Examples of old models that may be reused include standard components (e.g., screws) or proprietary parts that are important to a brand's recognition and aesthetic. When designers make a copy of an old model to save time, instead of modelling it from scratch, they may not realize that the model is linked to other documents such as old drawings, macros, or assembly files that must then be manually updated to reflect the new design (ID9, ID11, ID17). Often this creates more hassle than just recreating the original CAD model. As ID11 explains, *"I took an old part and I saved a new part as that part into a new name and that caused me many issues because that part was linked to a drawing already, so I truly should have just started from scratch, and I spent more time trying to make sure the attributes were reflected. [...] It was ridiculous."*

Managing dependent files can further create problems when a designer needs to take over the work of another designer who is temporarily unavailable (e.g., due to illness or vacation) (ID1, ID2,

[2]"Checking out" a file gives a user exclusive edit authority of the file until it is checked back into the system. While the file is checked out, other designers can view, edit and make copies of the file but are not permitted to save any modifications in order to prevent merge conflicts.

ID5, ID8, ID10). If the model is referenced in other models and the new designer is unaware of these links, unintended modifications can be created to other assemblies (ID2, ID5, ID9, ID15, ID18).

Challenge 4: Lack of awareness of collaborators' model changes

During concurrent work, a CAD model may be edited by more than one designer, not necessarily at the same moment in time, but close enough in time that there are numerous and frequent design contributions from different team members. Interviewees reported that they lack awareness of others' changes, and they have to manually keep their local "checked out" files up to date to avoid conflicts, duplicate work, or overwriting each other's edits, which significantly decreases their working efficiency. For example, designers modelling near-concurrently must be conscientious to regularly refresh the CAD program or monitor the file repository to ensure that they are working with the most current version of the model, since a new version of the file or dependent files could have been uploaded by a different designer in the meantime (ID16, ID18). Additionally, when edits made to a model do not propagate to teammates in real time, conflicting versions could be developed. Therefore, the designer must manually close and reopen the file to reveal the new change (ID2, ID3, ID13, ID15, ID18). Thirdly, multiple designers may create a CAD model for the same part, not knowing that they are doing duplicate work (ID16). ID2, a designer who collaborates directly with 10-15 other designers, said that "*there are some headaches [with] teams working and updating their parts in real time [because] you don't always know exactly what's the final interface or final geometry for certain things. There will be problems where some team updates something and doesn't tell the other team and then you have to quickly turn back and make certain design changes or change the layout of your part, because now everything is clashing with each other.*"

Challenge 5: Lack of support for synchronous editing of CAD models

In some collaborative work contexts, such as synchronous design review meetings, multiple designers may want to experiment with minor changes to a design in real time, but the CAD platforms they use do not support synchronous editing (ID1, ID4, ID18, ID20). The ability to edit synchronously is valuable for maintaining awareness and coordination amongst collaborators. Although third-generation collaborative CAD packages support real-time synchronous editing, none of our 20 interviewees report using them. We further discuss collaborative CAD and its role in addressing collaboration challenges in Sec. 5.2.

Strategy 2: Using assembly configurations. As a workaround to synchronous editing, designers may use assembly configurations as a "*lower commitment way to experiment with design changes, compared with creating a new version*" (ID16) – in other words, a way to maintain links and traceability while creating a variant from a standard version of a model. Configurations are intended to allow designers to create multiple variations of a part or assembly within a single CAD file, such as different dimensions, material properties, features, or even positions of parts within an assembly (e.g. laptop lid closed and open configurations) [95]. However, ID16 proposes another purpose of assembly configurations – to serve as personal sandboxes for each designer to test different design concepts (such as the fit of new parts into an existing assembly). With this method, the original configuration of the assembly remains unaffected, and designers are able to experiment within their respective configurations without fear of impacting the work of another designer.

4.2 Synchronous Communication Challenges

A critical component of effective collaboration is communication, which is defined as the act of sharing or exchanging information between two or more people [67]. The two challenges presented in this section pertain to the difficulties designers face when conveying and discussing contents and intent of CAD designs during synchronous meetings. Of the 20 interviewees, 10 mentioned challenges with synchronous communication.

Challenge 6: Cumbersome presentation of CAD models in synchronous work settings

One of the most important instances of communication is design review meetings [18]. Design reviews can bring together the core design team to explore ideas, coordinate tasks and provide updates, while larger, less frequent reviews involve other stakeholders such as clients or collaborating organizations [4, 108]. Presenting live CAD models during synchronous meetings can be challenging because: (1) it takes some level of trial and error to adjust the angles of the model for optimal viewing (ID6, ID16, ID17, ID18); (2) it can be time-consuming to manually maneuver the model to show specific perspectives, cross sections of parts, and to hide/view components (ID4, ID6, ID15, ID16, ID17, ID18); (3) live CAD is not ideal for communicating certain design features such as products with very thin cross-sections (e.g. laptop lid) (ID17). As explained by ID16 who spends 10% of their time collaborating synchronously, "*even though [the designer is] the most familiar with the design so it should be easier to navigate [the CAD model], it is ultimately always really clunky and slow to hide all of the [parts] and find the right position. It would definitely be really nice if people could just check the CAD themselves, but not everyone is as familiar with how to use the tool so it's not really feasible. But I think there's a lot of opportunity to figure out how to enable other people to interact with a model in a more friendly way, like in the context of doing a design review.*"

Depending on stakeholders in attendance, designers will accordingly adjust the way they show their design. In design review meetings with a core design team who have technical CAD backgrounds, designers may opt for showing the live CAD, where they are able to manipulate the model and make edits in real time (ID4, ID17). Although there are advantages to showing a live CAD model during a design review, interviewees state that providing feedback in this manner can be slow, because only one individual at a time (typically the person presenting) can make edits to the model (ID4, ID11). That being said, three interviewees suggest that design reviews are more efficient when conducted remotely, since all observers have the ability to annotate (e.g., scribble and add comments) the CAD model from their screens directly (ID4, ID6, ID16).

For relatively formal meetings with non-technical stakeholders (e.g., clients), designers may instead opt to present a slideshow containing images of the design, since curated images are more reliable than live CAD in terms of technical difficulties (ID8, ID11, ID13, ID15, ID16, ID17). However, designers risk not being able to deliver the entire understanding of the model with 2D images alone. As put by ID18, a designer who frequently collaborates externally, "*Sometimes I'm sharing the design with people who don't have as much CAD experience and the result is that they don't visualize things the same way as me. I don't really know what it is that the person I'm showing my design to doesn't understand or wants to see more of, and they aren't sure either. There's always a gap.*"

Challenge 7: Lack of support for real-time conceptual design with CAD

When initiating a new project, some designers meet with their client to discuss the client's request and brainstorm potential designs. In these client meetings, ID12 expresses that it can be difficult to interpret the client's vision into a detailed design because designers and clients typically use hand sketches to convey ideas, and these drawings can overlook detailed design features (ID12). When asked why CAD is not used during these meetings, ID12 explains that creating conceptual designs directly in CAD (also known as conceptual CAD) simply takes too long — a common but conventional criticism of conceptual CAD [41, 103]. As ID12 explains, "*it's possible to freehand CAD and share screen to design while [the client] is talking if it's a small change [which] just takes two to three minutes. But if it is only 10 to 15 seconds that the client is available for, it is difficult for me to* *update the changes.*"

4.3 Data Management Challenges and Strategies

CAD data management involves sharing, storing, and managing CAD files and related documentation such that they are accessible and interactive for the team and stakeholders [109]. In CSCW literature, data management tools are known as groupware for *information sharing*, that "enable interaction through a shared document or collection of documents" [82]. Challenges coded into this category relate to issues that designers have with storing and retrieving shared files, file versions, and file dependencies. In total, 17 of 20 interviewees mentioned five data management challenges and five strategies.

Challenge 8: Lack of CAD software and CAD data management interoperability

A frequent challenge mentioned by 12 of 20 interviewees is the lack of CAD software interoperability, meaning that models created in one CAD platform cannot be edited in another. This lack of interoperability can be challenging not only when designers use different mechanical CAD (MCAD) software or even different versions of the same CAD software (ID5, ID6, ID9, ID10, ID14, ID15, ID18), but also when both MCAD and EE CAD are used. Components created in other types of CAD (such as printed circuit boards or wire harnesses modelled in EE CAD) can be impossible to import into an assembly in MCAD if the CAD software does not support cross-platform integration (ID1, ID9, ID10, ID11, ID13, ID16, ID20). Consequently, designers cannot directly visualize how components will interact and whether interfaces of components will conflict.

The data management of both MCAD and EE CAD parts is additionally challenging because EE CAD parts may be stored in a different PDM system than mechanical CAD (MCAD) parts, so retrieving parts from each location is a tedious and manual process (ID17). Furthermore, EE CAD parts may be managed by a different VCS (version control system) from the one used for MCAD files, which creates opportunities for the MCAD model versions and non-MCAD model versions to become unsynchronized, especially if both designs are still evolving (ID1). As ID1 explains, "*The version control of both platforms is OK, it's reasonable. [The challenge] is syncing up the version control of both systems at the same time.*" Keeping the versions in lockstep relies on the diligence of the designers to promptly update each other when a new version is created so the change can be reflected in the other VCS.

Strategy 3: Converting to neutral CAD file format. Converting files into a neutral, MCAD-readable format, such as STEP or STL is a way to address the lack of CAD software interoperability (ID3, ID5, ID6, ID9, ID11, ID12, ID20). A major drawback of this strategy is that neutral file formats erase all model history. Without a comprehensive history of the design, future designers who may revisit the model will have to spend more time understanding the design intent. However, participants also report that during external collaborations, files are intentionally converted into neutral CAD formats, as the model histories, feature trees, and other design data that is erased is often proprietary to the company (ID2, ID6, ID9, ID10, ID14, ID16, ID17, ID18, ID20).

When given a neutral CAD file (sometimes called a dumb solid), often from a supplier or other external collaborator, designers find it worthwhile to spend the extra time to parametrically reverse engineer the dumb solid so that it can be editable for future use (ID9, ID14, ID15, ID16, ID17). Regarding the importance of using parametric CAD models, one interviewee said, *"because I didn't really have the time to [recreate the model], I just ended up working off of the [dumb solid], even though it's not ideal, and maybe a future person would have the same dilemma. It was a hacky, non-ideal, non-best practices solution"* (ID16).

Strategy 4: Creating simplified versions of CAD models. Simplifying a CAD model entails creating a version of the model with some details or features removed. Although simplifying a model is often used to minimize the computer processing time and power required to generate the model (ID4, ID8, ID17), interviewees also reported that they simplify models when EE CAD parts are involved in an assembly. Since the lack of CAD software interoperability prevents EE CAD parts to be directly imported into an MCAD assembly, designers will recreate the electrical part as a simple block that can be added into the main assembly model (ID11, ID13, ID16).

Challenge 9: Lack of change summarization support between file versions

Often, designers want to review the design history of a CAD model or revert to a previous version of a CAD model (for example, after prototyping and testing) (ID6, ID10, ID13). Tracing back the version history of a design is challenging because typically no documentation summarizes the changes made between model versions, so designers cannot easily identify how two versions differ and what changes were made within each revision (ID1, ID5, ID17, ID18). Two interviewees share that their team maintains a document, such as an Excel spreadsheet, to log the modifications made between versions, but this is a tedious task that relies on designers to manually examine both versions and record the changes, and to do it promptly, while the designer still remembers the modifications they made (ID5, ID18). ID18 said, "*the hardest thing with going back to a previous [model] version is keeping track of what you actually changed in each version. Usually, I'll put notes into my 2D drawing that's associated with that file to say I edited these things, but sometimes you change a lot of stuff and you don't track everything [...] which becomes really cumbersome. [...] We'd have to refer to some other document where we're keeping track of the changes, but it's not associated or linked in any way to that [CAD] file.*"

Challenge 10: Lack of version control and centralized data management for non-PLM users

As mentioned in Section 3.2, four of our interviewees do not use formal data management tools (i.e., PLM systems). For these teams, the lack of automated naming conventions for files and folders or standards for folder structures makes it difficult for stakeholders to locate the latest version of a file (ID5, ID11, ID14, ID19, ID20). If the correct version cannot be found, a designer will need to modify an older model version to reflect the new changes (ID3, ID5). Designers may also mistakenly work on an incorrect version of a model, thinking it is the latest version, resulting in wasted work (ID7, ID20).

Design teams that rely on manual data management tools (e.g., Dropbox) face further challenges when models are frequently accessed by multiple collaborators. Because there is no check in/check out system to ensure only one designer can edit a model at a time (as described in Challenge 2), designers will create a copy of the shared model and edit locally on their workstation, then upload the model to the shared drive once completed. With this workflow, designers may accidentally overwrite each other's work when uploading or create merge conflicts (ID6, ID7).

Strategy 5: Using formal data management tools (e.g., PLM). There are mature, commercially-available, formal data management tools (e.g., PLM) that automate the version control process and facilitate file sharing among collaborators. As previously described, with *conservative* configurations of PLM, checking out a single file automatically checks out all other files linked to it; for example, checking out a part model also automatically checks out the assembly model that contains the part, which eliminates the risk of merge conflicts. However, in *less conservative* PLM configurations, designers are able to edit a model and the drawing or assembly linked to the model separately, which creates the possibility for the files to become out of sync (ID2, ID7, ID13, ID14, ID15, ID16). When files become out of sync, this can lead to lack of awareness of collaborator's model changes, as described in Challenge 4. To avoid this issue, ID16 says that best practices are to check out the entire assembly, even when only editing a single part.

Challenge 11: Poor CAD file organization for multi-use models

Two interviewees mentioned that with their team's file management structures, all files pertaining to the same project are organized within a single folder; this structure does not facilitate using a component in multiple projects (ID16, ID20). Consequently, designers will make copies of the CAD file to insert in each project folder which causes issues with CAD part proliferation; as one interviewee points out, *"[a designer] may recreate the part, give it a slightly different naming convention and then we have two copies of the same part so over time, we just have a ballooning list of parts and nobody really goes in to clean it up"* (ID16). Another flaw with this workaround is that CAD models become independent when a copy is made — as if they are two distinct components. As such, edits made to one file do not propagate to all (ID5, ID20).

Strategy 6: Using standard part libraries. Standard part libraries were discussed by three interviewees as an effective way to catalogue and control shared parts and to keep them updated for all team members across all projects (ID10, ID11, ID16). ID10, an interviewee who started their own design company, explains, "*when we create the model in India in the [PLM], we name it '70-millimeter screw with hexagon head', so if you search from Germany, '70-millimeter screw', the same part will come. So, the same part can go into multiple assemblies, you can use it anytime [and] because it's a standard part, once it is created, it will never change. [...] We created a standard parts library for washers, for screws, for nuts, and for many other things and I would encourage that for CAD collaboration – it's very important to have standard parts libraries.*"

Challenge 12: Poor traceability of scattered file management

When designers want to quickly share progress with their teammates, they may send screenshots of their models back and forth with annotated comments/edits, also called *redlining*. Interviewees state that while this process is common, it can be challenging because redlining is not formally documented or controlled by a PLM system (ID5, ID11). Since these screenshots are usually sent through email or instant messages, records of design changes have low traceability and can be easily lost. Similarly, documentation and comments are not directly integrated into the CAD file, which means that: (1) designers must remember to upload and retrieve these files separately; (2) a designer is tempted to upload a CAD model without also uploading the proper documentation to save time or meet a deadline, which results in a decrease in overall design quality and traceability (ID9); and (3) documents can become unsynchronized, which creates issues with file versioning (ID1, ID2, ID9, ID18, ID20). As explained by ID20, *"for some of the more aesthetic stuff, there's just no good way of representing that in CAD so a lot of those details get lost unless you have the accompanying documents with it, but then those two things can be out of sync and that makes it harder to hand off things."*

Strategy 7: Using integrated digital markup tools. Some CAD platforms include integrated digital markup tools that allow users to directly create comments and notes in the CAD file, so all of the design information pertaining to a single model can be centralized, thus improving design traceability, though only one interviewee reported using this feature (ID5).

4.4 Permissioning Challenges

Although both data management (Sec. 4.3) and permissioning challenges (Sec. 4.4) pertain to *information sharing*, we chose to categorize these challenges separately because as in other CSCW fields, their causes are inherently different [75]. Data management challenges are limited by the tools themselves – such as the features of the tool or the tool's ability to support human-computer interaction. On the other hand, challenges with permissioning are highly informed by the needs of the people of the organization; simply improving tooling support cannot resolve permissioning challenges. Of the total 20 interviewees, 13 mentioned challenges relating to permissioning.

Challenge 13: Cumbersome stakeholder access to CAD files

15 of 20 interviewees reported that their teams restrict the edit authority of designers to increase the traceability of modifications and prevent accidental overwriting of files. Assigning edit authority can be accomplished in many formal data management tools like PLM systems (Strategy 5). Under this structure, a designer who takes over another designer's project must be granted access to the project file(s) by either the original designer, team manager, or administrator, depending on how the PLM system is configured (ID1, ID7, ID8, ID11, ID13, ID14, ID18). While this issue can be resolved relatively quickly, it still imposes an additional step during the trade-off of responsibility and can delay the design process.

It is common for external collaborators to lack access to the file repository — PLM system or otherwise — so cross-company collaborators must resort to an external online file-sharing service like Dropbox or Google Drive (ID5, ID6, ID7). Since these platforms lack version control support, it can be challenging to recall specific versions (ID2, ID6, ID10, ID11, ID17) and stakeholders seldom have access to the most recent version of CAD files; because uploading files to an informal data management system is a manual and thus tedious task, interviewees report that files may be updated as infrequently as once a day or even once a week (ID16, ID17, ID18).

Challenge 14: Lack of stakeholder access to CAD software

For a variety of reasons (e.g., lack of licenses, specific role of stakeholder in the company or differing conventions), stakeholders may not have access to CAD, so they are not able to review the design (ID6, ID7, ID16, ID18). In this situation, these stakeholders must rely on those who have CAD access to convert the file into accessible formats, such as screenshots and 2D drawings.

This lack of access is common when temporarily employed contractors are involved in the development pipeline. To protect the intellectual property of the company, contractors may be given limited access to CAD platforms. For example, a contractor may only be given SolidWorks CAD access, whereas the rest of the team primarily models in NX CAD; so, a contractor would be unaware of design changes that are made in NX CAD (ID11).

5 DISCUSSION

In this section, we discuss the main findings of our work. We first elaborate on the general trends of the identified CAD collaboration challenges to propose suitable solutions. Then, we consider the potentials and pitfalls of cloud-based collaborative CAD to resolve collaboration challenges. Finally, we conclude this section with the limitations of our study.

5.1 Potential Solutions to Collaboration Challenges

In this study, 14 collaboration challenges were found to be impeding professional CAD teams. Here, we discuss three potential methods of resolving these challenges – best practices, tooling support, and management & processes. Table 1 summarizes the challenges and our proposed solutions.

5.1.1 Best practices. Best practices are procedures or guidelines that are generally accepted as superior than other alternative methods, and are used in all industries, including software development [26], and CAD [14]. We propose that the development and enforcement of best practices serve as a promising solution to Challenge 1: Absent or varied modelling conventions across collaborators, and Challenge 2: Infrequent model uploads prevent contribution from collaborators. Although best

Table 1. Summary of 14 challenges found through the interviews, with sources included where a challenge has been previously referenced in either grey or academic literature. Each challenge is categorized by our proposed solution, either best practices, tooling support, or management & processes.

Proposed solution	Type of challenge	Challenge number: Name of challenge	References in literature
Best practices	Collaborative design	1: Absent or varied modelling conventions across collaborators	[9, 38]
		2: Infrequent model uploads prevent contribution from collaborators	
Tooling support	Collaborative design	3: Lack of designer awareness of model dependencies	[34]
		4: Lack of awareness of collaborators' model changes	[13]
		5: Lack of support for synchronous editing of CAD models	[68, 81]
	Synchronous communication	6: Cumbersome presentation of CAD models in synchronous work settings	
		7: Lack of support for real-time conceptual design with CAD	[103]
	Data management	8: Lack of CAD software and CAD data management interoperability	[34, 56, 105]
		9: Lack of change summarization support between file versions	
		10: Lack of version control and centralized data management for non-PLM users	[13, 34, 39, 68]
		11: Poor CAD file organization for multi-use models	[39, 84]
		12: Poor traceability of scattered file management	
Management & processes	Permissioning	13: Cumbersome stakeholder access to CAD files	[18]
		14: Lack of stakeholder access to CAD software	[6, 18]

practices are our proposed solution for only two of the total 14 challenges, Challenge 1 and 2 are collectively mentioned by 18 of 20 interviewees, suggesting they are quite significant.

Defining best practices in the CAD collaboration workflow. In our study, it was found that a considerable CAD collaboration challenge is varied conventions between designers, which necessitates the development of unified best practices for CAD. Many CAD companies have published modelling best practices to help standardize and optimize modelling techniques [54, 69], but the prevalence of Challenge 1 and 2 in our results suggest that these existing best practices are either not enforced or are inadequate for addressing the needs of all CAD teams.

A contributor to the complexity of defining best practices for CAD is the various dimensions of the design process that introduce variability amongst designers. Rosso et al. showed that sources of variability in the CAD design process include: (1) *file size* (number of possible combinations of features to achieve the same part), (2) *modelling time* (total amount of time taken in building or editing a model), (3) *total operations* (log length), (4) *operations per second* (modelling rate), (5) *complexity* (the amount of effort it would take another designer to understand the model), *features* (number), (6) *features* (order), (7) *features* (types), and (8) *completeness* [86]. However, these eight measures may be a gross over-simplification of CAD variability because they only pertain to the modelling aspect of CAD design. Further variability is introduced in the data management aspect of the CAD process. Therefore, comprehensive best practices for CAD must also include guidelines for data management, such as: file structure and organization, file naming standard, layering standard, annotation standard, external referencing standard, plot standard, and shared part libraries [69].

Some interview participants mentioned that their team provides a CAD standards and best practice document, however, none of these interviewees report formalized enforcement or continued training of these best practices, which greatly reduces their efficacy. Of the 20 CAD professionals we interviewed, only one reported a company-wide standardized modelling procedure, and this initiative took two to three years to accomplish. Evidently, establishing and successfully enforcing best practices is a large challenge that CAD teams must overcome, but a first step that CAD professionals can take is to enforce team-wide best practices. We therefore call for future CSCW research to enhance the adoption rate of team-wide best practices.

Tackling technical debt. Technical debt is a term that has been used in software development to describe the implied cost of future rework caused by taking a shortcut to speed up development [57]. Some of the major causes of technical debt are schedule pressure, carelessness, lack of education, poor processes, nonsystematic verification of quality, or basic incompetence [57]. To tackle technical debt during the software development procedure, researchers and practitioners suggest maintaining awareness of technical debt and its causes, keep track of technical debt, properly manage technical debt, and quantify the impact of technical debt from various aspects, such as interest, business risk, liability, etc [25, 61]. Similar to software development procedure, technical debt is also a useful lens for observing inefficiencies at different stages of the CAD design lifecycle. Rosso et al. studied "CAD smells" – the CAD equivalent of code smells in software to identify symptoms of violating design principles that can affect the long-term quality of a code or CAD, or in other words, lead to technical debt [87]. An example of technical debt in the design process occurs when a designer neglects standardized modelling conventions, proper referencing, commenting, and/or documentation, and a future designer who edits the CAD model faces difficulties understanding and then modifying the original design (Challenge 1). Therefore, our results suggest that a fruitful area for future research is to systematically understand technical debt during CAD design, to quantify the cost, derive best practices, suggestions, and even checklists to identify technical debt as early as possible.

5.1.2 Tooling support. Among the 14 challenges we found, we propose that 10 challenges can be addressed with better tooling support in the key areas of improving awareness for designers, facilitating traceability of documentation, supporting file dependency management, and improving synchronous design communication. We recommend that tool builders target the challenges presented in this paper in future iterations of CAD and CAD-related tools to better support the collaboration practices of CAD practitioners today.

Awareness tools. When a team's size becomes large or team members collaborate in a distributed setting, it is common for designers to be unaware of what others are working on, which is the *lack of awareness* problem that has been studied previously in distributed software development scenarios [16, 28, 35, 46, 90, 101]. The interview participants in our study reported similar challenges when multiple designers need to edit the same model or models that interact. Due to lack of awareness of other's changes, designers have to manually refresh their local workspace frequently to avoid conflicts, duplicate work, or overwriting each others' edits, which significantly decreases the working efficiency. Therefore, more research is needed to develop awareness tools that can help team members to maintain an overview of the activities and even automatically identify and resolve potential conflicts, similar to the awareness tools that has been developed to increase the awareness in software development teams [85, 89, 111]. Our findings contribute new insights to the existing body of CSCW literature to better understand the CAD collaboration workflow, and design implications for enhancing awareness in distributed CAD teams [62].

Facilitating traceability to avoid scattered information. During the CAD collaboration workflow, team members use multiple communication channels (e.g., email, Slack, SharePoint, shared drives) to share ideas and updates, and even make decisions. However, this information is rarely organized in a centralized location; such scattered information harms traceability of the product's development process, which further decreases the working efficiency (Challenge 12: Poor traceability of scattered file management). One could argue that this can be mitigated by following better practices, i.e., by manually documenting all the pieces of information systematically. However, this level of documentation would be time-consuming and tedious. Therefore, we recommend development of a tracking system that can be connected with the PLM system or integrated into the design teams' workflow.

File dependency management. Dependency management has been widely studied in software development procedure. The number of interdependencies among files and activities during the process is one of the major challenges that harms the working efficiency and security of a software system [10, 30, 31]. Researchers have developed tools to analyze and visualize technical dependencies to decrease developers' extra workload and facilitate communication among development teams [29]. The tools support the dependency management at different levels, such as at file level [43], feature level [22], or source code level [48].

As reported in our study, designers often use older files as a starting point for new designs, or coordinate files between multiple projects. Due to Challenge 3: Lack of designer awareness of model dependencies, users have to manually update linked artifacts if the dependency information is missing, or they might accidentally change others' designs due to a hidden dependency. Currently, only a subset of PLM systems provides an overview of all assembly files that contain a single model. However, of the 16 interviewees that use PLM, only one interviewee reported use of this feature. Another strategy that can mitigate this challenge is to restrict edit authority of a model to a few designers to avoid unexpected changes and encourage teammates to frequently update their progress with others. However, this strategy does not scale, significantly slows down the progress and is contrary to the philosophy of collaboration. Therefore, inspired by the dependency management studies mentioned above from software engineering, we believe it is important to build tools that automatically track CAD artifact dependencies and send warnings to designers who might trigger unexpected changes, ultimately avoiding costly rework.

Improving design communication. The presentation of live CAD models occurs in nearly all design review meetings and is a task that designers encounter often. However, many interviewees report that CAD — a powerful design tool — is not in its current state well-suited to be used as a communication tool. Tasks such as maneuvering the model to show specific angles, hiding and showing components, and presenting certain design features are all troublesome or *"clunky"*, as ID16 puts it. Thus, we recommend that tool builders reconsider the needs of CAD practitioners — not only robust design features but communication features too.

Automating various workflow activities. Overall, the development of new, effective tools can help automate tasks that are otherwise difficult, time-consuming, or tedious for designers to do manually. Challenge 10 is an example of how several problems can arise when teams do not use fully-automated version control tools like PLM to manage CAD artifacts, such as manual versioning, possibility of overwriting work, and lack of centrality of documents. Our findings show that these issues are mitigated in teams that use PLM tools. From the success of PLM for automated version control, we can extrapolate that the automation of other cumbersome design activities, such as the generation of change summaries between file versions (to address Challenge 9) would also be beneficial to the CAD workflow process.

5.1.3 Management & processes. Challenges in this category can be addressed with better management and processes. Both Permissioning challenges are related to stakeholders having the correct access to necessary files and tools, which is the responsibility of team administrators and project managers. Similarly, addressing *Challenge 1: Absent or varied modelling conventions across collaborators* could be supported by proactive management via training, encouragement, and incentives for developing and following team- or company-wide best practices.

5.2 Potentials and Pitfalls of Third Generation Collaborative CAD

As previously mentioned, the goal of this study is to understand current collaborative practices with CAD tools in professional product design teams, where distributed CAD is still the industry standard. However, we recognize the existence and growing attention paid to third generation collaborative CAD tools like MUCAD and cloud-based CAD platforms which partly aim to address the long-standing collaboration challenges that we present in this work.

Third generation collaborative CAD migrates locally installed standalone CAD systems to the cloud for easier file sharing and enables different-place, same-time collaboration [33, 47]. Due to its unique capabilities, we speculate that collaborative CAD is able to resolve a subset of the challenges discussed by our interviewees. Notably, collaborative CAD addresses many data management challenges, such as: lack of CAD software interoperability (Challenge 8) because cloud CAD automatically updates users with the latest version of the software [8]; and lack of version control and centralized data management (Challenge 10) because the cloud data storage enables access from any designer at any workstation and backups of CAD files are automatically created and stored for streamlined retrieval. It is even suggested that cloud-based collaborative CAD can alleviate the challenge of lack of stakeholder access to CAD software (Challenge 14) because it is browser-based (not hardware-dependent) and licenses can be assigned to the number of concurrent users and not the total number of users, thus increasing the availability of CAD licenses [6]. The collaborative design challenge of lack of support for synchronous editing of CAD models (Challenge 5) has been addressed with synchronous MUCAD tools like Onshape and Fusion360, though researchers are still assessing whether MUCAD improves or reduces the efficiency of design [32, 38, 79, 80]. It has also been suggested that design teams using collaborative CAD have greater awareness of team members' activities since edits to a model can be seen by collaborators in real time [38]; however other studies have shown that the degree to which awareness is increased is still insufficient for effective collaboration (primarily due to lack of overview of design activity) [19] – thus more work is needed in the development of awareness tools for CAD designers.

Despite the aforementioned benefits, we do not anticipate that product design teams will eliminate all collaboration challenges by simply implementing collaborative CAD. From our study, we have shown that common collaboration challenges faced by CAD designers include lack of awareness collaborator's actions and model dependencies (Challenge 3 and 4), cumbersome presentation of live CAD models in synchronous meetings (Challenge 6), absent or varied modelling strategies (Challenge 1) that complicate model transfer between collaborators and thus lead to technical debt. These relate to fundamental CSCW challenges like lack of awareness [16, 35], difficulty communicating synchronously [45], and difficulty developing and enforcing best practices within teams [97, 112], and are faced by all three generations of CAD.

The inability of collaborative CAD to completely solve these challenges has been evidenced by previous studies. Eigner et al. assessed the usefulness of Onshape – a cloud-based MUCAD tool – in student design teams and found that communication between distributed collaborators remains a large challenge, even when supplemented with other collaboration platforms like Slack or WhatsApp. With poor communication, the designers lacked awareness of each other's actions which "led to problems regarding the collaborative tasks" [36]. Zissis et al. described that a challenge that new collaborative CAD tools must overcome is poor interactivity and visualization of 3D models during distributed synchronous collaboration settings, like design reviews [113]. As for varied modelling conventions and low enforcement of best practices, adopting cloud CAD or MUCAD will not directly solve these problems. However, developing unified best practices within design teams and proper management to enforce them may be a viable solution, as discussed in Sec. 5.1.1.

Furthermore, there are additional challenges with the actual transition from distributed CAD to collaborative CAD, which are not covered by the challenges described in this work. Disrupting the traditional, well-established processes of the existing CAD workflow and routine in itself is a large undertaking [8, 60]. Design companies are generally keen to introduce time- and money-saving technologies and are likely aware of these third generation collaborative CAD systems. Yet, collaborative CAD systems hold only a fraction of the market share compared to distributed CAD (around 10-20% for professional design firms) [65, 104]. Reportedly, companies are hesitant to transition to collaborative CAD due to lack of confidence in the successful implementation of the new technology, concerns over data security and loss, difficulty in learning and using the new technology, cloud service availability issues and the cost of using cloud services [72].

Overall, we conjecture that design companies are averse to change and reluctant to stray from their current reliable workflows, even when they may be vulnerable to challenges. Supporting this notion is the observation that our interviewee pool represents a wide demographic of organizations, including many world-leading, innovative companies in the aerospace, automotive, and electronics industries, as well as small-scale companies, yet none use collaborative CAD. We therefore imagine a future where middle-ware products can help enhance the collaboration capabilities of standalone and distributed tools for some companies, while other companies move towards fully collaborative CAD systems. We anticipate that our description of challenges, and our suggestions for potential solutions will be a first step towards the development of these solutions for efficient and effective collaborative design with CAD.

5.3 Limitations

The first limitation of our study is the gender balance in our interviewee pool. The World Economic Forum reports that in 2020, only 15% of global engineering professionals were women [3]. Women represent an even smaller percentage within key CAD-dominant engineering roles: 4% of design and development engineers, 5% of mechanical engineers and 12% of draughtspersons [106]. In recognition of the under-representation of women present in both real-world data and our first 10 interview participants, we actively sought to recruit women CAD practitioners during the second half of our interviews to ensure that our findings are inclusive of their insights. Thus, there is a degree of sampling bias in our study.

A further limitation to our study is that the advertisements used to recruit participants and the interviews themselves were in English. The lack of representation of non-English speakers may have a notable impact on our findings. For example, a large demographic of CAD users are based in China (roughly 10% of the global CAD market) but this was not reflected in our interviewee pool [2]. A few of our interviewees confirmed that they frequently collaborate with Chinese CAD designers, so it is in the interest of future work to include the experiences of designers who are fluent in any language, not just English.

Another consequence of our sampling method is the absence of input from CAD designers in additional industries known to rely on CAD (e.g., defense or marine). Similar to the aerospace industry, products created by engineering designers in the marine industry are also extremely large and complex, which can exacerbate challenges to collaborative design. It is therefore important to investigate collaborative design practices in all engineering design industries in future studies.

In any case, interviewing a larger and more diverse sample of participants will increase the generalizability of our findings. However, interview studies rely on the availability of CAD professionals and their willingness to participate in a study that does not offer compensation for their time. Nonetheless, consensus was found across our participants of various industries, roles, and levels of seniority, suggesting that the collaboration challenges and strategies presented in this paper are indeed prevalent within the CAD community.

6 CONCLUSION

In this study, we interviewed 20 CAD professionals to better understand collaborative practices in physical product development. Challenges and strategies involved in CAD collaboration practices were systematically categorized into themes of collaborative design, communication, data management, and permissioning.

From our interviews, we confirmed major CAD collaboration challenges previously reported in literature, such as: lack of CAD software interoperability; poor CAD file organization for multi-use models; and varied modelling conventions between designers. Our main contribution is our discovery of new, previously unreported challenges and inadequacies of current tools, management choices, and best practices to support the demands of today's CAD practitioners. Our notable findings include:

(1) Varied modelling conventions across collaborators is a common challenge that can occur which causes technical debt. Researchers in other fields — such as software development — have proposed best practices to resolve technical debt [57], and the same is needed for CAD. That said, regardless of which best practices are proposed, formal enforcement is required in order to realize the full benefits of implementing best practices to avoid technical debt.
(2) Poor documentation management leads to low traceability of the CAD design process which causes CAD documents to be lost or scattered — a severe impediment to efficient product development. Advancements in improving traceability of CAD documents is vital for future iterations of data management tools.
(3) Designers face difficulties presenting live CAD models in design review sessions because CAD software, by design, is a drafting and modelling tool, not a communication tool. Yet, CAD is often used by designers to communicate design information. Therefore, it is important for tool builders to recognize how designers use CAD for all purposes — not only modelling — to better support effective communication.
(4) Current CAD tools lack the support for change summarization between CAD file versions, so tasks like retrieving the desired file version or understanding how two versions differ are tedious and inefficient. With the iterative nature of product development, creating and revisiting design versions is inevitable, thus targeted development is needed in this area.

As the development of modern products becomes increasingly complex, demanding, and globalized, it is imperative for researchers, practitioners and tool builders to understand not only how CAD collaboration is evolving, but also the challenges engineers face in the current landscape of collaborative product design. With the insights gained from our work, we hope to ultimately improve collaboration efficiency, quality, and innovation for future product design teams, and we welcome a new, collaboration-focused paradigm of CAD.

6.1 Future Work

Costs of CAD collaboration challenges. This study provides a systematic review of CAD collaboration challenges to help the CAD community understand what challenges designers face in the collaborative workflow. Aspects of the design process were found to be challenging for different reasons. For example, when a designer mistakenly works on the incorrect file version due to poor file management, time and effort are wasted and rework is necessary. When a designer has trouble showing the optimal angles of their CAD model, time is lost in design review meetings, which may shorten the time that stakeholders have to give feedback, resulting in a lower quality final product or longer overall development time. In all cases, there is an impact or *cost* associated with these collaboration challenge. Anecdotal evidence has found that costs of poor collaboration can include:

wasted time and effort, downstream errors, lost designs (intellectual property), missed design due dates, and missed design budgets [13].

At this point, we have only built a qualitative understanding of the costs of CAD collaboration challenges. Further work is required to quantitatively measure or *operationalize* the costs of poor collaboration practices. Although little was found in the literature on CAD collaboration costs, a prior study conducted by Tiong et al. evaluated the tradeoff between design information gained through prototyping and the resources (time, cost and effort) expended [99]. By definition, prototypes convey design information that allow a team to advance "in product development with minimal expenditure of time and cost", and thus CAD models can be considered as a digital prototype [15]. In their study, Tiong et al. introduce methods to quantitatively analyze the relationship between the amount of time spent doing a task and the value gained from the task (in this case, the task is prototyping) [99]. In future work, we aim to take a similar approach to quantify and compare the time spent doing a design activity with and without best practices, management, and tooling support. These insights will not only determine the economic costs of CAD collaboration challenges, but also identify which challenges are the most costly and therefore urgent to resolve.

Translating concepts from software development. The broader motivation for our research was to not only classify challenges of CAD collaboration, but to also compare CAD collaboration challenges to collaborative software development challenges. Although software development is inherently different from CAD design in terms of the shared artifacts and final product (digital versus physical), both fields encounter challenges caused by distributed teams and asynchronous work. The parallels between these two fields have similarly motivated recent studies in the investigation of open-source hardware (OSHW) to mimic open-source software (OSS) [91], the adaption of DevOps ('Developer Operations') to open development of hardware, creating 'HardOps' [94], and a mapping between code smells and CAD smells [87]. Relative to collaboration with CAD, collaborative software development, of both challenges and mitigation strategies, has been well-studied, with successful implementation of suggested solutions and best practices [98]. Through investigating analogies between challenges of CAD and software development, we hope to find broadly applied best practices and strategies used in the software development field that can be applied to CAD with the goal of alleviating challenges in a novel way.

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A INTERVIEW PARTICIPANT INFORMATION

Here we provide detailed information on the interview participants (Figure 1). It should be noted that three of the total 20 interviewees did not respond to our post-interview follow up survey, so we are unable to provide complete information for collaboration and CAD knowledge characteristics.

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	Demographics					Tools Characteristics		Collaboration Characteristics				CAD Knowledge Characteristics	
ID	Gender	Role	Industry	Exp. (Yrs)	Company Size	CAD Software Used	VCS Type Used	Number of Simultaneous Projects	Number of Collaborators	Time Spent Collaborating Externally	Time Spent Working Synchronously	Knowledge Updating Frequency	Knowledge Channels
ID1	M	Project Engineer	Aerospace	11	Large	AutoCAD, NX, OrCAD	Full	1	3 - 4	5 - 10%	50%	Rarely	Colleagues, company training
ID2	M	Mechanical Design Intern	Automotive	2	Large	CATIA, Creo	Full	2	10 - 15	5 - 10%	40 - 60%	Occasionally	Colleagues, company training, forums
ID3	M	Mechanical Designer	Building	1	Large	AutoCAD, Revit	Full	6 - 8	3	10%	10%	Occasionally	Company newsletters, company training
ID4	M	Mechanical Engineer	Aerospace	3	Large	Fusion 360, NX, SolidWorks	Full	4 - 6	1 - 8	0% for design activities 90% for design reviews	20 - 75%	Regularly	CAD vendors, forums
ID5	M	Designer Engineer	Nuclear	5	Small	SolidWorks	Manual	1 - 3	1 - 5	0 - 10%	10%	Occasionally	Blogs, forums
ID6	M	Mechanical Designer	Signage	2	Small	SolidWorks	Manual	2 - 3	1 - 2	25%	30%	Regularly	Blogs, forums
ID7	M	CAD Specialist	IT Infrastructure	10	Small	AutoCAD, Civil 3D	Manual	3 - 8	4 - 6	0%	40%	Regularly	Blogs, forums, online tutorials, user manuals
ID8	M	Design Engineer	Automotive	7	Large	CATIA	Full	2 - 4	8 - 10	15%	5 - 10%	Regularly	Forums, CAD vendors
ID9	M	Product Development Engineer	Automotive	16	Large	AutoCAD, Creo, CATIA	Full	1 - 10	3	10 - 30%	10%	Occasionally	Colleagues, company training
ID10	M	CEO	Materials	20	Small	Creo, Fusion 360	Full	4 - 6	3 - 4	40%	40%	Regularly	CAD vendors, forums
ID11	F	Mechanical Designer	Aerospace	2	Large	NX, SolidEdge	Full	2 - 3	1 - 5	10%	5%	Rarely	Colleagues
ID12	M	Mechanical Design Engineer	Electronics	6	Large	CATIA, Creo, SolidWorks	Full	2 - 5	1 - 8	15%	15%	Occasionally	Blogs, colleagues, online tutorials
ID13	M	Test and Integration Engineer	Aerospace	4	Large	NX	Full	3 - 4	50	5%	5%	Rarely	Online tutorials
ID14	M	Senior Mechanical Engineer	Electronics	25	Large	NX, SolidWorks	Full	N/A	N/A	N/A	N/A	N/A	N/A
ID15	F	Test and Integration Engineer	Aerospace	2	Large	NX	Full	3 - 4	10	5%	5%	Occasionally	Colleagues, online tutorials
ID16	F	Mechanical Engineer	Medical Devices	6	Large	SolidWorks	Full	N/A	N/A	N/A	N/A	N/A	N/A
ID17	F	Mechanical Engineer	Electronics	16	Large	Creo	Full	1	3 - 30	0% for design activities 90% for design reviews	25%	Occasionally	Colleagues, company training
ID18	F	Product Design Engineer	Electronics	6	Large	NX	Full	1 - 2	5 - 14	25%	10%	Occasionally	Company training
ID19	M	Systems Engineer	Automotive	1	Large	CATIA	Full	1 - 2	2 - 3	10%	5%	Occasionally	Colleagues, online tutorials
ID20	M	Senior Mechanical Engineer	Consumer Goods	10	Large	SolidWorks	Manual	N/A	N/A	N/A	N/A	N/A	N/A

Fig. 1. Summary of characteristics of interview participants, including information regarding demographics, CAD tools used, collaboration characteristics, and CAD knowledge.

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