**ORIGINAL PAPER**

# "Why couldn't we do this more often?": exploring the feasibility of virtual and distributed work in product design engineering

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## Abstract

Lower costs and higher employee satisfaction are some of the benefits driving organizations to adopt dispersed and virtual working arrangements. Despite these advantages, product design engineering teams—those who develop physical products—have not widely adopted this working style due to perceived critical dependence on physical facilities and the belief that it is ineffective to communicate technical details virtually. This paper uses the mass shift in working conditions caused by the COVID-19 pandemic to explore the feasibility of virtual and distributed work in product design engineering. We conducted 20 semi-structured interviews with product design engineers working virtually to uncover current challenges of, and the beginning of promising strategies for, effective virtual engineering work. We categorize and analyze Tangible Design activities, Intangible Design activities, and Communication and Project Management activities throughout the product design process. Contrary to present opinions, we found that much of a product design engineer's work is realizable in a virtual and distributed setting. However, there are still many challenges, especially when attempting Tangible Design activities—those that require physical products and tools—from home. These challenges, missing from existing virtual product design engineering literature, include but are not limited to individuals' lessened sense of accountability, fewer de-risking opportunities before product sign-off, and limited supervision of production staff. Product design engineers described novel strategies that emerged organically to mitigate these challenges, such as creating digital alternatives for engineering reviews and sign-offs and leveraging rapid prototyping. Recent advances in technology, an increased commitment to reducing environmental impact, and better work-life balance expectations from new generations of workers will only push society faster towards a distributed working model. Thus, it is critical that we use this opportunity to understand the existing challenges for distributed product design engineers, so that organizations can best prepare and become resilient to future shocks.

**Keywords** Virtual work · Work-from-home · Product design · Physical products · Mechanical engineering

## 1 Introduction

Can physical products be designed and developed by teams working together virtually, from home? While working in a distributed and virtual manner is gaining popularity in many industries, especially software development, there seems to be an assumption that *product design engineering*—the creation of physical products, sometimes referred to as hardware, electromechanical, or mechatronic engineering—cannot succeed in this new way of working.

In fact, only 3% of the 5 million American employees who worked from home half or more of the time in 2016 were from the manufacturing sector (Global Workplace Analytics 2020a). Globalization is increasing the frequency of virtual collaboration; however, the benefits of lower costs, better work-life balance, and higher job satisfaction are felt mostly by those in professional, scientific, technical, or financial services (Committee on Information Technology Automation and the U.S. Workforce 2017; Global Workplace Analytics 2020a). Product design engineers have not adopted the work-from-home model due to the need to access physical facilities for prototyping and testing (Velzen and Olechowski 2021), fear of leaking critical intellectual property (IP) assets (Ding et al. 2009), and the belief that communicating highly technical details is only possible during face-to-face communication (Eppinger and Chitkara 2009).

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Although product design engineering teams themselves are typically co-located, they are no strangers to the motivation for virtual collaboration; many researchers have written about the strategies for and the effect of adopting a more globalized product design approach. However, these studies discuss a phased implementation of this new process that often requires clusters of co-located work (Lakemond and Berggren 2006; Eppinger and Chitkara 2009; Montoya et al. 2009; Song and Song 2010). The increasing popularity of global product design engineering has even prompted the study of how to teach global collaboration to engineering students and prepare them for the workforce (Brisco et al. 2019). Thus, most existing approaches and models of distributed product design engineering differ from the entirely dispersed model described in this work.

COVID-19 has forced engineering firms to shift to the extremes of this working style overnight, adopting an entirely virtual and completely dispersed organizational structure. This situation raises an interesting opportunity to explore the question of the applicability of previous global product design engineering research to today's working paradigm, and whether workers can successfully apply approaches from the existing body of literature in this extreme environment.

Prior work on virtual hardware-dependent teams is limited, but we can extend the existing virtual collaboration theories to illuminate the unique needs of product design engineers. Previous research provides evidence that task type can influence the success of virtual teams, and should inform decisions surrounding collaboration strategies and communication tools (Martins et al. 2004; Maruping and Agarwal 2004; Dennis et al. 2008; Montoya et al. 2009; Stone et al. 2018; Golden and Gajendran 2019). With these findings in mind, we should be careful not to paint all product design engineering projects with the same brush; various activities and task types are involved in the design process, which would be affected uniquely by virtual work. For this reason, we use the product design process as our lens to study the diverse challenges and strategies in the development of a physical product by a virtual team.

While only 3.6% of the working American population worked from home half or more of the time in 2016, these numbers are estimated to have jumped to 25–30% by the end of 2021 due to the feasibility demonstrated during the COVID-19 pandemic (Global Workplace Analytics 2020b). This widespread shift to virtual work allows us to study the adapted product design engineering skills, processes, and organizational arrangements (Marion and Fixson 2021). We believe that valuable lessons can be learned from product design engineers that likely would not otherwise have attempted completely virtual and distributed work.

The contributions of this work are as follows: We present one of the first studies of widespread virtual work for professional product design engineers who design physical hardware products, with a specific focus on how this dependency challenges their adoption of a virtual or distributed working arrangement. Second, we identify the beginning of promising strategies for product design engineers to continue with this working style in the future. Finally, we identify persisting challenges, under-discussed in the literature, which represent promising directions for future work in this field.

## 2 Background

Virtual work is a richly studied topic, with a significant foundation of insight from which to draw. Gibson and Gibbs (2006) define virtuality by its four characteristics: geographic dispersion, electronic dependence, structural dynamism, and national diversity. While most prior research classified teams as either virtual or not, Martins et al. (2004) contrasted this by explaining that all teams fall somewhere on the spectrum of virtuality. Furthermore, the term 'dispersion' is frequently used in virtual work literature, where it may refer to geographical dispersion, temporal dispersion, or cultural dispersion (Morrison-Smith and Ruiz 2020). When describing teams, the literature often uses 'virtual' and 'dispersed' or 'distributed' in conjunction, as dispersed teams rely more heavily on virtual communication.

In this paper, we will use the terms *"virtual"* and *"distributed"* or *"dispersed"*; however, terms such as *"remote work," "distance collaboration," "teleworking,"* or *"computer-supported collaborative work"* also apply to our setting. We contrast these terms with our definition of *"global product development teams,"* which consist of clusters of co-located work and cross-functional global collaboration. This work explores virtual teams at or near the extreme of Martins' spectrum of virtuality (Martins et al. 2004): teams that communicate and collaborate almost exclusively via technology. Furthermore, our interviewees reflected on their experience working on teams that are entirely geographically dispersed, meaning that individuals work independently in their homes.

### 2.1 Distributed hardware projects

Most research on entirely distributed engineering teams focuses on software projects (Gilson et al. 2015), where virtual work is prevalent and often successful. In contrast, researchers argue that co-location is necessary for innovative product design engineering (Mascitelli 2000). Bellotti and Bly (1996) suggest that product design engineers should be co-located because of their high levels of local mobility: they move around the office to communicate, collaborate, and maintain awareness. Even when researching distributed new product development teams,

**Fig. 1** The product design process used as a framework in this study (adapted from Ulrich et al. 2020)
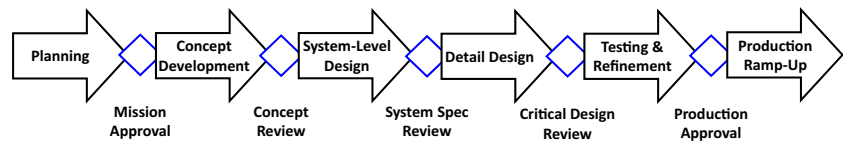


some researchers discuss a choice between co-locating either product teams or functional teams, but not entirely dispersed teams (Lakemond and Berggren 2006). One critical barrier to distributed product design engineering work is access to physical parts, prototyping tools, and testing laboratories (Velzen and Olechowski 2021). However, the recent advances in rapid prototyping tools such as 3D printers, and a wide variety of online vendors, have made it possible to prototype complex products from a home studio (Camburn et al. 2017), presenting the possibility for physical product designers to work from home.

Some researchers argue that physical distance between team members is negatively correlated with communication frequency (Leenders et al. 2003). A previous study found that chance encounters with people from different teams within the same firm, which are much less frequent in distributed settings, increase exposure to other people's thoughts and generate new ideas (Sailer 2011). Mascitelli (2000) argues that because of the sharing of "tacit knowledge," a powerful source of innovation, design teams should be co-located whenever possible. Similarly, a recent study of new product development teams' research and development efforts during COVID-19 also highlights how limited face-to-face interaction prevents critical tacit knowledge transfer (Cecchi et al. 2022). In addition to knowledge transfer, virtuality was also found to increase the complexity of a team's shared mental model (Schmidtke and Cummings 2017).

On the other hand, other researchers suggest that the relationship between physical distance and team outcomes is more complex and depends upon contextual factors, such as project duration or level of innovation (Lakemond and Berggren 2006). For example, El-Tayeh et al. (2008) concluded that although virtual design teams exhibited more variability, there were few statistically significant results in the performance of virtual versus in-person teams. Since product design engineering is rarely a solitary endeavour, it stands to reason that the relationship between team proximity and communication, collaboration, and knowledge sharing will likely affect a team's ability to develop elegant solutions for complex challenges.

One of the few studies of virtual product design engineers investigated the minimum functional requirements for a collaboration tool used by designers and suppliers in the automotive industry (May and Carter 2001). Though this paper is relatively old, the resulting functional requirements remain pressing even today: high-quality audio, a collaborative 2D whiteboard tool, online access to Computer-Aided Design (CAD) files and project documents, and simultaneous CAD viewing capabilities. While we can apply some existing virtual work findings in product design engineering contexts, a study specifically focused on product design engineers' potential to work virtually is lacking.

## 2.2 Task-technology fit and the product design process

Due to the heavy reliance on virtual communication in geographically dispersed teams, media capacity theories (matching task requirements to media characteristics) influence much of the virtual work literature (Dennis et al. 2008). These theories have formed the basis of multiple virtual team studies that propose task-technology matches to improve communication effectiveness.

Previous work has often described trends in product design as a whole, despite the distinct nature of the work and decisions being made in each of the process's sub-phases (Krishnan and Ulrich 2001). Many models describing the product design and development process have been developed over the years, each relaying different purposes and points of view (Wynn and Clarkson 2018). For this study, we decided to select a generic version of the product design process (Fig. 1) which consists of six phases: Planning, Concept Development, System-Level Design, Detail Design, Testing and Refinement, and Production Ramp-Up (Ulrich et al. 2020), similar to other phase-based investigations (Fernandes et al. 2015; Goetz et al. 2020). We can consider this process a series of specific tasks; therefore, task-technology fit theory would suggest that each phase of the product design process would have unique technology needs that organizations must address to maximize effectiveness. In the following paragraphs, we connect previous task-technology fit recommendations to the types of tasks often performed in different phases of the product design process.

Montoya et al. (2009) studied product design engineers in industry and argue that technology fit depends not only on the task type but also on the situational environment. The authors propose general guidelines for tool choice based on the product development tasks' goals, but do not map these tasks directly to phases in the product design process. On the other hand, Stone et al. (2018) recommend specific tool attributes for each phase of the product design process based on a study of distributed undergraduate engineering capstone teams. Early phases, such as Planning and Concept

Development, require rich media with low response times to build trust in new teams and converge on a concept. Middle phases, such as System-Level Design and Detail Design, require permanent tools that allow longer response times to communicate highly technical concepts. Late phases, such as Testing and Refinement and Production Ramp-Up, require media that can be operated in parallel, are easily accessible, are permanent, and have a short response time, so that teams can coordinate efforts between members, manufacturers, and suppliers. Brisco et al. (2018) identified five categories of Computer-Support Collaborative Design (CSCD) technologies and their impact on different aspects of design activity, including input knowledge and resources. Not specific to tools, another study investigated in which of the product design process phases teams should co-locate and found that project definition and product launch benefitted most from co-location, and teams can be located functionally during detailed design and verification without impacting efficiency (Lakemond and Berggren 2006).

We can use task-technology fit theories to hypothesize how to improve specific tasks within the product design process. This theory indicates that we might expect to uncover challenges at the task level from product design engineers as they shift to a virtual working arrangement.

## 2.3 Successes and challenges of virtual work

In many contexts, virtual work has been associated with positive outcomes; working virtually has resulted in higher quality projects and decisions, less time to make decisions, and more unique ideas generated (Gilson et al. 2015). One study found that the percentage of time per week spent working virtually was positively associated with increased job performance, particularly for highly complex roles that are low in interdependence and social support (Golden and Gajendran 2019), perhaps similar to product design engineering work. Most notably, the authors concluded that working virtually is not detrimental to job performance across various job characteristics.

A key component of product design engineering is creativity; however, there is no consensus on how this is impacted by virtual work. Some researchers suggest that virtual collaboration will increase creativity due to allowing more time for individual brainstorming and the chance to share ideas anonymously (Thompson 2021). Contradicting this, Chulvi et al. (2017) found no statistical difference in expert ratings of usefulness or unusualness between conceptual designs from in-person and virtual teams. Furthermore, recent research has shown that videoconferencing narrows a participant's cognitive focus, limiting creative idea generation (Brucks and Levav 2022). It has been shown that the environment combined with individual personality types

and thinking styles contribute to the degree of novelty of conceptual designs, suggesting that the relationship between virtual work and creativity might not be the same for every product design engineer (Mulet et al. 2016; García-García et al. 2019).

Researchers have also discussed the downsides of the future digital workplace (Chinowsky and Rojas 2002; Colbert et al. 2016; Golden and Gajendran 2019; Morrison-Smith and Ruiz 2020). Colbert et al. (2016) demonstrated that virtual workers have a harder time focusing on intense problem-solving or creative work, both of which are at the core of product design engineering. On the other hand, Golden and Gajendran (2019) concluded that a role's problem-solving dependency is not a factor in its ability to be completed virtually. Recent virtual team literature (Morrison-Smith and Ruiz 2020) identifies many of the same managerial challenges experienced by virtual engineering teams—such as communicating expectations, controlling long discussions, and losing sight of project objectives—that were identified almost 20 years ago (McDonough et al. 2001; Chinowsky and Rojas 2002).

Thus far, much of the virtual work research intends to provide a list of best practices for effective virtual teams in industry. Literature suggests that future digital workplaces will need to leverage employee competencies and motivation, encourage mindful use of technology, and take advantage of new technologies to simulate in-person communication (Colbert et al. 2016). Similar to this work, Lumseyfai et al. (2019) empirically developed a framework of five themes for engineering teams involved in virtual projects, although they did not target entirely virtual and distributed engineers. This framework included technology integration, virtual resource management, project governance controls, stakeholder engagement, and organizational drivers.

Despite the interest in virtual teams from Psychology, Organization Science, Innovation, and Engineering researchers, there still exist gaps yet to be addressed (Gilson et al. 2015; Morrison-Smith and Ruiz 2020). Gilson et al. (2015) identified themes for future virtual team research that are touched on in this work: the creation of virtual teams due to circumstance; whether challenges are caused by virtuality or inexperience with technology; the effect of new and emerging technologies on virtual work; and transition processes and planning. Additionally, the rapid pace of communication technology development requires that we revisit existing findings, as recent advances in technology can significantly impact the distributed teams that use them (Committee on Information Technology Automation and the U.S. Workforce 2017).

While researchers have studied virtual teams to a great extent, virtual product design engineering teams are rarely studied nor attempted in industry (Global Workplace Analytics 2020a). When researchers do focus on virtual product

**Table 1** Participant characteristics

| # | Gender | Industry | Design phases | Country | Role | Organization size |
|---|--------|----------|---------------|---------|------|-------------------|
| 1 | M | Medical | 1, 2, 3 | CAN | Manager | Medium |
| 2 | W | Manufacturing equipment | 4, 5 | USA | Project/Program Manager | Medium |
| 3 | M | Manufacturing equipment | 3 | USA | Project/Program Manager | Medium |
| 4 | M | Automotive | 2, 3 | USA | Sr. Technical | Large |
| 5 | W | Automotive | 1, 2, 3 | USA | Technical Systems Engineer | Large |
| 6 | M | Aerospace | 3 | USA | Technical | Large |
| 7 | M | Displays | 3 | CAN | Technical | Small |
| 8 | W | Medical | 2, 3, 4 | USA | Sr. Technical | Large |
| 9 | M | Consumer goods | 0, 1, 4, 5 | CAN | Sr. Technical | Large |
| 10 | M | Nuclear | 2, 3 | CAN | Technical | Small |
| 11 | M | Power | 0, 1, 4, 5 | CAN | Manager | Medium |
| 12 | M | Electrical devices | all | USA | Technical | Large |
| 13 | W | Automotive | 2, 3 | USA | Sr. Technical | Large |
| 14 | M | Medical | 4, 5 | USA | Manager | Small |
| 15 | W | Consumer goods | 3, 4 | CAN | Project/Program Manager | Medium |
| 16 | M | Medical | 2, 3 | CAN | Sr. Technical | Small |
| 17 | M | Nuclear | 3, 4 | CAN | Technical Systems Engineer | Large |
| 18 | W | Electrical devices | 1, 2, 3 | USA | Project/Program Manager | Large |
| 19 | W | Automotive | all | USA | Technical Systems Engineer | Large |
| 20 | M | Aerospace | 0, 1, 2 | CAN | Manager | Large |

design teams, it is often in terms of global organizations with co-located design teams that collaborate with manufacturers and suppliers overseas (Eppinger and Chitkara 2009; Montoya et al. 2009). Researchers have not targeted entirely virtual and distributed physical product design teams. Product design engineering includes distinct activities, yet virtual work literature in this area has yet to identify the unique challenges by activity type and how design teams could mitigate these challenges. Furthermore, we must revisit previously identified challenges of virtual work while accounting for newly emerging tools (Marion and Fixson 2021), particularly considering the digital transformation fast-tracked by the COVID-19 pandemic (Marr 2020). Our study aims to fill these research gaps.

## 3 Methods

We conducted 20 virtual semi-structured interviews to examine the unique challenges of virtual work experienced by product design engineers in each phase of the product design process. We conducted interviews over a 3-month period from June to August of 2020. We then qualitatively analyzed the data as universal and critical challenges and strategies emerged.

## 3.1 Participants

The interview sample consisted of 20 product design engineers. We recruited participants who worked in an engineering context on hardware products and excluded those who worked as independent contractors or primarily in software. As this work represents the discovery and description step in theory-building research (Cash et al. 2022), we purposefully sampled participants through our professional networks first. All of those contacted through the researchers' networks participated or offered another candidate. To expand our sample, we then recruited via an email to the alumni of a research-intensive Canadian university engineering program, specifying our inclusion criteria and asking participants to complete an initial survey providing additional details on their organization, role, and current level of virtuality. The recruitment email was sent to 6842 alumni, with a 74% open rate and an 8% click-through rate, with 30 alumni responding to our request with interest in being interviewed. From those 30 alumni who responded positively to the email recruitment, we chose seven to complete the interview based on the diversity of industry and reliance on hardware products. This resulted in our final interview sample, from both recruitment methods, consisting of 7 women and 13 men, spanning 16 different companies in ten industries. Participants had all worked at their company prior to the COVID-19 imposed work-from-home regulations, and only one participant had changed teams while working from home. Participants

spanned roles from entry-level designers to vice presidents, which allowed us to gather a wide range of perspectives and further compare and contrast findings across roles (Szajnfarber and Gralla 2017). A summary of participants is shown in Table 1, along with the relevant sample factors. Participant role is categorized into five levels: Technical and Sr. Technical, which represent various seniorities of mechanical designers; Project/Program Managers, which represent those who manage mechanical projects, but not people; Managers, who manage both projects and people; and lastly Technical Systems Engineers, who work in a technical role, with much of their job being the coordination of output from others. Small organizations are defined as organizations with fewer than 100 employees, between 100 and 999 employees for medium-sized organizations, and 1000+ employees for large organizations (Gartner 2022). Design phases are labelled with 0 (Planning) to 5 (Production Ramp-Up), corresponding to the diagram in Fig. 1.

## 3.2 Material

Qualitative methods are suggested for use in engineering work when a phenomenon is new or poorly understood (Szajnfarber and Gralla 2017; Yin 2018), such as the feasibility of virtual work in product design engineering. Semi-structured interviews provide enough structure to address specific topics relating to virtual work while being flexible enough for participants to offer new study foci (Galletta 2013). We administered the interviews following a guide approved by the University of Toronto's research ethics board.

The interview guide was developed to address the following research question: *how have virtual working conditions impacted hardware-dependent product design engineers?* We started by asking general questions about the background of the participant's company, work, and virtual collaboration experience prior to COVID-19. The participants were then shown the model of the product design process shown in Fig. 1, developed by Ulrich et al. (2020). Participants self-identified the phases they had been primarily working in during the virtual work period and were asked to respond to interview questions in the context of these phases. We then inquired more specifically about their most significant challenges in these phases and the tools and strategies they used to address them. We also explored their attitude towards virtual work prior to COVID-19, and presently, and how their team dynamics have evolved with interactions moving online. Interview questions were pilot tested within the research team and iterated upon to ensure that they sufficiently addressed the guiding research question and were clearly worded.

## 3.3 Procedure

We conducted the interviews via Whereby,[1] a video-conferencing software. Two-to-three researchers were present in each interview in the event of technical difficulties; however, one researcher was designated as the primary speaker for each interview to ensure that the questioning continued smoothly. Additional researchers were present to interject with follow-up questions where appropriate. Interviews lasted approximately one hour and were transcribed using the Rev autotranscription service.[2] As this research began with a guiding question and not specific hypotheses, as we interviewed more participants, we made minor adaptations to the interview guide to include additional probing questions around themes that were beginning to emerge (Szajnfarber and Gralla 2017; Babbie 2020). The interviews were conducted in blocks, with responses evaluated after the first block, when it was determined that new challenges and strategies were continuing to emerge. New challenges and strategies ceased to emerge after the second block of interviews when knowledge saturation had been reached. While having a standard set of questions allowed comparison and classification across interviews, the flexible nature of semi-structured interviews allowed us to explore emerging themes further.

## 3.4 Analysis

We used the qualitative research software NVivo[3] to analyze the data by identifying quotes relating to specific themes and assigning them to "codes." The first author conducted a preliminary analysis across all transcripts, coding discussions of challenges and strategies. As many participants worked through or supervised multiple phases during the virtual work period, the challenges and strategies they spoke about related to multiple different phases. Thus, after the initial analysis, the entire research team revisited the compiled list of challenges and strategies and used consensus discussion to determine which phase of the product design process each specific challenge or strategy referred to, given the phases that the participant identified in the interview. However, during this process, we recognized that many challenges and strategies spanned more than one phase, and a more useful framework could be used to categorize these findings instead. Three researchers used consensus discussion to decide whether each challenge and strategy referred to: an Intangible Design activity—an activity specific to the product design process that does not rely on physical products,
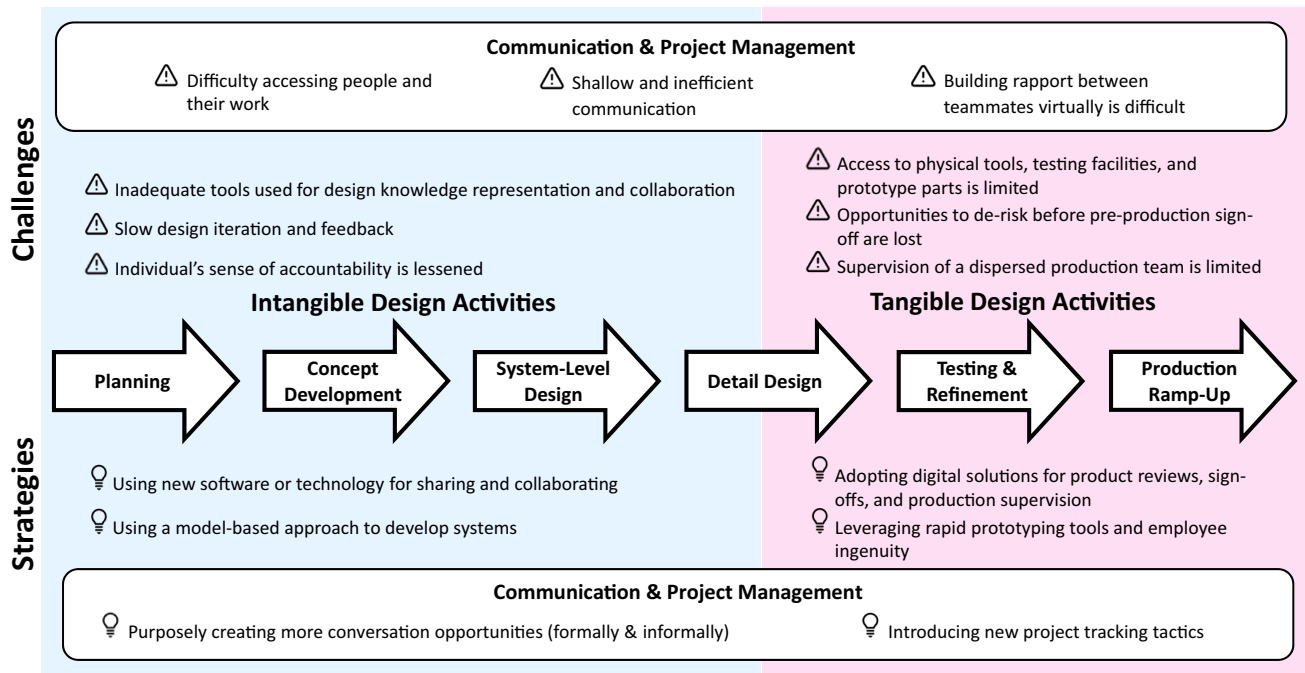
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**Fig. 2** Summary of challenges and strategies, presented by activity type

prototypes, tools, or facilities; a Tangible Design activity—an activity specific to the product design process that does rely on physical products, prototypes, tools, or facilities; and Communication and Project Management activities—activities that are not specific to one or more phases in the product design process, but critical to project success. Following this process, the three researchers then collectively compared results across participants to identify patterns between challenges and strategies and participant characteristics such as role and organization size. When reporting quotes in the following section, it should be noted that filler words such as "um" and "like" were removed without indication to improve readability.

## 4 Results and Discussion

We begin by discussing and providing evidence for our participants' prior widespread belief that virtual product design engineering was not achievable. Next, we divide our discussion of challenges and strategies by nature of the design activity. As evidenced by our analysis, and spoken directly by some of the participants, each virtual product design process activity came with unique challenges, and some were more conducive to a virtual work style than others. Participant 11 summarizes:

For the projects that were in the Planning or Conceptual Development phases, [virtual work] was an inconvenience, but you could generally get the work done. For the projects in Testing and Refinement and Production Ramp-Up when no one could go in, there isn't really a good substitute for that [when] work[ing] from home. (Participant 11)

Thus, we highlight critical challenges to, and strategies specific for, virtual work in three distinct areas of the product design process: (1) Intangible Design activities, (2) Tangible Design activities, and (3) Communication and Project Management activities. Note that participants did not share strategies for every challenge discussed, and thus, not every challenge presented has a corresponding strategy. We finish our results and discussion with evidence of a mindset shift in product design teams. Although common virtual work trends emerged as themes in our interviews (e.g., insufficient internet and virtual private network speed, logistics of setting up remote permissions, separating work and home life, creating a work-from-home setup, and caretaking burdens of childcare), we will focus our discussion on those topics critical and specific to product design engineering. For an in-depth look at the impact of virtual work on work-life balance, see Palumbo (2020). Figure 2 summarizes the key challenges and strategies presented in this paper, organized by Intangible Design activities, Tangible Design activities, and Communication and Project Management activities.

## 4.1 Initial attitudes towards virtual work

Out of the 20 product design engineers that we interviewed, 15 discussed the previous perception of the impossibility of working from home; this was a belief either personally held, or a policy of their organization. The participants explained that they did not believe it was possible to work primarily virtually, nor were their organizations prepared with policies and processes to manage this working style prior to the work-from-home mandate. Our participants explained that it was a "once in a blue moon kind of thing that people would work from home (Participant 17)." Participants detailed that this was due to the nature of their work and their reliance on laboratories and physical prototypes: "Because we are such a hardware-focused company, we had generally discouraged [working from home] (Participant 2)."

Others explained that the reluctance to work from home was more of a mindset or cultural phenomenon: "one of the cofounders really equated numbers of hours in the office to how hard people were working (Participant 16)." Most participants expressed that their organization had limited work-from-home procedures in place prior to COVID-19, and employees could only work from home in exceptional circumstances. This pattern was specifically noted by Managers and those participants who were part of small organizations.

We observed additional patterns in attitudes: Those who worked in global organizations—which tend to be large and in mass-production industries such as manufacturing equipment, automotive, and consumer goods—and regularly used communication technology to collaborate with other satellite offices, overseas suppliers/manufacturers, or remote coworkers, were more confident in their ability to work virtually more of the time. Participant 4 explains, "It was already pretty common to have every meeting web-based, … there's already so many people that are in different offices, and physical locations that work on-site at a [company office], but not everyone's concentrated in one building." Participants also discussed aspects of their roles that they believed would make virtual work more challenging. Participant 19, a Technical Systems Engineer, describes, "a lot of my job is managing projects and things… I thought it would be difficult to do not in person."

While we did not find any research directly related to product design engineers' attitudes towards virtual work , studies of related fields—such as scientific research—that rely on access to physical labs and spaces have discussed the unavoidable interruption caused by a forced work-from-home policy due to the inaccessibility of hardware equipment (Buchanan 2021). In our context, product design engineers have previously been described as locally mobile: they spend a lot of their day moving around the office to maintain awareness, discuss with colleagues, build and test, or locate parts (Bellotti and Bly 1996). The longstanding belief that

product design engineering must be done in-person was reflected in some of our participants' organizations; a lack of trust of employees (Kaplan et al. 2018), as well as the shared belief that virtual work is ineffective, can prevent employees from attempting it (Laumer and Maier 2021). However, consistent with recent COVID-19 virtual work literature (Bai et al. 2020), those participants whose organizations had embraced virtual work on some level prior to the pandemic, were less opposed to the idea. Having organizational support and the tools needed to conduct the job remotely influences workers' attitudes towards virtual work (Laumer and Maier 2021).

## 4.2 Challenges and strategies for Intangible Design activities

We define Intangible activities within the product design process as those that do not principally rely on physical products, prototypes, or tools. Regarding the process shown in Fig. 1 (Ulrich et al. 2020), Intangible Design activities tend to fall in the Planning phase, Concept Development phase, System-Level Design phase, as well as any activities in the Detail Design phase that do not depend on physical prototypes and tools. Intangible Design activities include assessing potential technologies, setting up supply chain strategy, and allocating project resources in the Planning phase; clarifying customer needs, generating and evaluating product concepts, and developing conceptual designs in the Conceptual Design phase; developing product architecture and defining major sub-systems and interfaces in the System-Level Design phase; and digitally defining part geometry, or creating and modifying CAD files in the Detail Design phase (Ulrich et al. 2020). As some Intangible Design activities may be similar to activities in other knowledge work more broadly, not all of the challenges and strategies in this section represent challenges and strategies unique to product design engineers designing physical products. Of the 20 participants interviewed, 18 discussed challenges of Intangible Design activities.

We found that most of the product design engineers we spoke to shared challenges associated with Intangible Design activities, suggesting that portions of their work do not rely on physical products, but are challenging, nonetheless. Challenges present in these activities include difficulties when discussing and presenting ideas within the team or to external clients, being less vigilant when reviewing designs, slowed exchange of ideas and feedback, and problems retrieving and managing files. Although many Intangible Design activities can be performed individually or handed off between various engineers in succession, our participants highlighted the importance of collaboration for receiving feedback and reaching alignment. In a virtual work environment, engineers are unable to simply drop by

another's desk for a quick discussion as they would on a co-located team, which impedes real-time collaboration and instant feedback. The participants leveraged various strategies to adapt to virtual work for Intangible Design activities, including upgrading or adopting new screen-sharing tools, being more diligent in meetings, turning video cameras on, using a model-based approach to systems engineering, saving complete meeting minutes, as well as sharing models and drawings in advanced of meetings and design reviews.

Below, we expand upon the main challenges participants faced during Intangible Design activities and some of the strategies that can be used to combat these challenges.

*Challenge 1: Inadequate tools used for design knowledge representation and collaboration* Working in a virtual and distributed manner drove our participants to rely on software tools to carry out design activities and facilitate collaboration. However, many participants mentioned challenges resulting from inadequate design knowledge representation and collaboration tools. This common challenge was echoed across organization sizes, roles, and industries. Key examples raised by the participants included the lack of an effective virtual whiteboard alternative and difficulties with accessing and updating large CAD files.

The use of a virtual whiteboard was shown to be essential to digital engineering collaboration both 20 years ago (May and Carter 2001) and recently (Anderson et al. 2022). In fact, whiteboards are sometimes considered "boundary objects," which exist on the boundary of people and technology, and are particularly useful for knowledge sharing (Cecchi et al. 2022). Participant 20 described their experience using a whiteboard for sharing ideas with customers and working through use cases and scenarios in the Conceptual Design phase:

> The whiteboard is greatly missed … to meet with the customer and [share] ideas with them because that's really the best tool to work together…For instance, we have to [present] a lot of lifecycle [analysis], use case analysis, scenarios. It's all stuff from a whiteboard. We can do things like that with an application like VISIO, WebEx, et cetera, but it's not the same. (Participant 20)

Specifically, participants in our interviews shared that they miss physical whiteboards due to their speed, ease of use, ability to work collaboratively on one surface, and ability to communicate ideas in a "shared language" across different groups. Both participants who discussed their previous use of commercially available digital whiteboards to collaborate with global colleagues eventually abandoned these tools due to continuing lag and connectivity issues; indicating that even with the increase of solutions designed specifically for online collaborative teams, many participants still struggled to use virtual whiteboard alternatives during meetings.

Our participants described that virtual annotation tools result in poor sketches. Thus, they often switch to specific design tools such as CAD and screen-sharing, which can be effective but limit the variety of groups they can communicate with. Participant 16 described that sharing a CAD model can replace whiteboards: "sometimes by sharing a Zoom screen and then sharing my Solidworks window with a team…if it's the right group of engineers, they have the patience to let me sketch something in Solidworks…while we're just figuring out an idea."

Furthermore, CAD files are often a central part of the Detail Design phase. A common issue raised by interviewees was the technical difficulties they experienced when accessing and updating large CAD files, exacerbated by unstable company virtual private networks (VPN) and slow download speeds: "If you want to call up a CAD model, there's some lag, depending on your home computer hardware type of capability….The documents are not an issue, but when you deal with CAD, there's a lag (Participant 1)."

*Challenge 2: Slow design iteration and feedback* Another consequence of virtual work that challenges Intangible Design activities is the slow exchange of feedback between designers and protracted design iteration cycles. The design of an engineering product is highly iterative and requires constant refinement; hence, constant exchange of ideas and feedback is necessary (Wynn and Eckert 2017). However, in a virtual setting, it is difficult for engineers to bounce ideas off of one another or quickly obtain feedback on a design idea by dropping by a co-worker's desk. In our interviews, slow design iteration and feedback were brought up most often by those in Technical roles and those in medium and large organizations.

In the Concept Development phase, the impact of the slow exchange of feedback is most evident in the brainstorming process. As also noted in (Mascitelli 2000; Kniffin et al. 2021), participants experienced challenges creating and combining ideas. The reality of virtual work is that only one individual is able to express their ideas at a time, and therefore, bouncing ideas off of one another becomes problematic. Turn-taking is also an established detriment to conversation quality in knowledge work more broadly (Boland et al. 2021). This challenge is further exacerbated by a lack of visual feedback cues, such as body language, which is another common challenge with virtual meetings (Karpova et al. 2009). Participant 1 emphasizes these difficulties in the following statement:

> And usually what happens during a brainstorming meeting is [we get] synergies happening when you're talking about different concepts. Sometimes you come up with something on the spot, combining two or three concepts. [In a virtual setting] we have difficulty in formulating that; if you have a whiteboard, it [would]

be pretty easy that we can just draw it. But in the case of Zoom, we actually struggle. (Participant 1)

We heard evidence of this challenge particularly from those participants in industries where projects tend to be radical versus incrementally innovative (e.g., aerospace, display), as they are often solving new problems that they haven't seen before, for example:

The client comes to us and says, 'we have this problem. We want you to solve it.' And no one's kind of solved that problem before. So we have a lot of very unique challenges that we're just kind of coming up with creative solutions, when we run into difficulties every day and to kind of brainstorm on those ideas with your colleagues, it's a lot easier face to face. (Participant 17)

These experiences were recently confirmed using a large-scale laboratory study and field experiment: the authors found that videoconferencing inhibits the generation of creative ideas when compared to face-to-face brainstorming (Brucks and Levav 2022).

In addition to brainstorming challenges, our participants also reported challenges regarding reaching alignment when making project decisions, particularly in the System-Level Design phase, which often involves many stakeholders. This is an important challenge, as research has shown that successful product design requires many decisions (Krishnan and Ulrich 2001), and both employee roles and communication patterns can influence willingness to converge on these decisions (Antioco et al. 2008). Gathering required information, bringing together all stakeholders, and considering all perspectives becomes more challenging in a virtual environment. Participant 19 mentioned that "It becomes a little more difficult to coordinate between different people, to make sure that we get everybody aligned on the technical decision and [can] move forward."

Furthermore, feedback from peers and collaborators is crucial in the Detail Design phase as product design engineers update and refine their models. Traditionally, this process can occur formally during meetings and informally through quick conversations. Since the switch to virtual work, many of our interviewees described significantly more difficulty presenting their progress and receiving feedback on their designs and models:

The single most challenging thing I think would be the back and forth that my boss and I used to have on questions I had or suggestions I had regarding the modelling that I do…. Now it's not quite the same. I can send a screenshot over Microsoft Teams or something, and he'll respond, but it's a lot harder without being able to just point on a screen. (Participant 7)

The lack of timely feedback was exacerbated for new employees in high-risk industries, such as aerospace, nuclear and medical:

We were getting ready for our [novel mission] at the time as well. So you're dealing with a lot of risk and trying to figure out how to categorize that risk… for me being relatively new to the industry, it's kind of manifested in me overthinking that risk a lot. Whereas if I had been in the office, I would be able to talk to my manager or, you know, somebody who had been there for five years, and they could have talked me off the ledge and told me that this wasn't really a problem that we needed to focus so much attention on. (Participant 3)

As proven in literature, rapid feedback is critical for iteration in engineering design (Wynn and Eckert 2017) and is sought out frequently in traditional product design engineering teams (Bellotti and Bly 1996); however, this proved challenging for our participants when working virtually. To continue virtual product design engineering work, teams may have to create communication opportunities and policies that prioritize rapid design feedback.

*Challenge 3: Individuals' sense of accountability is lessened* Participants reported observing individuals taking a more hands-off approach when working virtually. When an issue is spotted, it becomes easier to stay silent and look the other way, thinking that someone else will resolve it. Whereas in a traditional in-person scenario, minor problems would be addressed immediately or assigned to someone after a quick discussion. In other fields, a similar challenge, which is termed social loafing—the act of withholding effort in teams—is especially problematic when working virtually (Rober 2020); however, it can be mitigated by increasing trust and control within the team.

This challenge was primarily discussed by Managers and Technical engineers in systems roles, and in medium and large organizations where a project may involve many teams. While this challenge was experienced in all industries, we found that those in highly regulated industries such as automotive and power discussed this most often. Participant 4 describes observing this phenomenon during his work-from-home experience in the quote below.

You're more hands-off unless you really fight against that. So if there's an issue, [you'll think]—'well, someone else will find that, or someone else will fix that.' Whereas when it's right in front of you, you have to fix it … but when you're working remotely, it's easier to stay silent and just let it slide. (Participant 4)

Participant 11 describes this challenge from a Manager's perspective:

I think it's easier for things to kind of be dropped, whether someone forgets or doesn't realize… It's a little bit less likely that people are thinking like, 'Oh, am I going to be the one that should do that' and kind of ask, 'Hey, who's following up on that.' So I am noticing…you have to be very diligent at the end to be like, 'here are the actions you're responsible for…can you do this?' (Participant 11)

*Strategy 1: Using new software or technology for sharing and collaborating* Whiteboards or physical drawings are often used during in-person brainstorming to communicate ideas readily. Many of our participants discussed their attempts to replicate quick idea sharing online when brainstorming. Unfortunately, few have found satisfying substitutes. Therefore, although literature suggests an abundance of alternatives for sharing and collaborating virtually, with Anderson et al. (2022) identifying 18 ways to replace the traditional whiteboard, it seems that the practicality of these solutions depends upon a case-by-case basis. As an exception, since starting virtual work, Participant 19 has invested in a tablet to freehand her drawings: "I was able then to download [Microsoft] Teams on my iPad and then draw while screen-sharing the iPad." By sharing her screen, she could better replicate the experience of sketching in front of her peers. Thus, organizations could consider investing in drawing hardware such as tablets and styluses, which our participants reported to be effective.

It has been shown in the literature that traditional collaborative cloud-based documents can assist in the collective generation of ideas (Jung et al. 2017). Similarly, our interviewees also shared some tools and strategies they found effective for reviewing CAD models and providing feedback. In particular, many adopted lightweight model-sharing by leveraging a cloud-based feature of CAD systems, allowing users to review a model without downloading the large file (Wu et al. 2015). This method for collaborative sharing and viewing of 3D CAD models would be particularly useful for the many design team members that need to review CAD models, but may not need to edit them themselves.

We used Onshape for CAD, and what was actually really great is they have a 'follow' command. So if you have the Onshape assembly document open, we can double click that person's icon at the top [if] they're on the same tab, and your screen will follow their mouse and all the motions they're doing. So that's how we would do a lot of the sharing and communicating. (Participant 3)

The use of new software and technology for sharing and collaborating was often discussed by those in non-management roles, which suggests that employees were taking the initiative to find new tools, or new uses for existing tools, to help alleviate some of their collaboration challenges.

This strategy reinforces the idea that organizations must invest in digital tools if they aim to move toward a more flexible working model (Madariaga et al. 2021; Anderson et al. 2022). Adopting new tools can ease the transition to a virtual work environment; however, some participants also reported that these tools could be challenging to manage and are time-consuming. Leaders should take heed of Marion & Fixson's (2021) warning to not overload staff with too many tools at work and look to literature (Dennis et al. 2008; Montoya et al. 2009; Stone et al. 2018) to optimize task-technology fit. Similar to our participants' adoption of new cloud-based design tools, Stone et al. (2018) also recommend using shared data editing tools in the middle of the product design process. As virtual collaboration tools are released into the market rapidly, researchers will need to study the impact of adding to a team's toolkit and the trade-offs of increased functionality.

*Strategy 2: Using a model-based approach to develop systems* Another strategy some of our interviewees employed was to use a model-based approach when developing complex systems, instead of the traditional document-based approach. With this approach, all the information needed for system development is captured in models that act as the single source of truth and can be accessed by everyone, regardless of location or phase of the product design process (Ding et al. 2009). By moving towards a model-based approach, teams can better manage system complexity, limit confusion, and improve traceability (Madni and Sievers 2018). This strategy can also prevent any uncertainties or misalignment between team members when making system-level decisions, so that sub-systems can be developed accordingly. Here, Participant 16 describes his company's approach: "We've definitely been trying to turn our company into a model-based company as opposed to a document-based company. And what that means is that all the information, the versions of truth, are our actual models instead of static images."

Model-based systems engineering (MBSE) has been identified as a solution to cope with the complexity of the global development environment of modern systems and to address challenges that arise from collaboration between geographically dispersed teams (Ramos et al. 2012). However, we found a lack of references that more directly investigate the link between MBSE tools for design and entirely distributed and virtual work; we anticipate this discussion being elaborated in the wake of the pandemic response.

## 4.3 Challenges and strategies for Tangible Design activities

We define the Tangible Design activities within the product design process as those that build, test, or otherwise require the use of physical products and tools. Based on the process shown in Fig. 1 (Ulrich et al. 2020), activities in this section include physical aspects of the Detail Design phase, such as selecting materials; the Testing and Refinement phase, including verifying prior design assumptions, validating performance, physical testing, and management sign-off; and the Production Ramp-Up phase, consisting of setting up the production operation, evaluating the production process and output before mass production, and travelling to offshore production facilities. The challenges and strategies referenced in this section are specific to product design engineers and the aspects of their job that rely on the physical interactions with products and equipment.

As expected, hardware-based engineering projects face more difficulty transitioning to a virtual work model. Although we noted previously that much of modern product design engineering work involves digital tools, every participant recognized the absence of physical facilities, tools, and parts as challenging. While this may seem like an obvious challenge for product design engineers, it is rarely or only briefly mentioned in the literature (Velzen and Olechowski 2021; Cecchi et al. 2022). Tangible Design activity challenges include delays in receiving parts, a lack of access to machine shops and part libraries, cost and logistical complexity associated with shipping parts, siloed decision making, difficulty arranging testing and training on new equipment, and challenges overseeing production activities. There are a number of characteristics of these activities that further complicate virtual work: product design engineers often rely on technicians for testing, which can be problematic if engineers and technicians have fewer communication opportunities. Although the product design process shown in Fig. 1 depicts testing as one phase completed after design, in practice, tests are conducted at various stages throughout product development, thus causing product development to be greatly impacted by virtual work (Tahera et al. 2019). Some Tangible Design activities may be impossible to duplicate virtually; however, they are essential, since these activities are the last chance to identify errors before production. Furthermore, the need to keep valuable intellectual property protected also restricts the ability to work on physical products remotely. Participants detailed newly adopted strategies such as complex camera setups, shifting working hours, and enhanced documentation to address these challenges. Below, we expand upon participants' main challenges and share strategies they have devised to alleviate some pain points.

*Challenge 4: Access to physical tools, testing facilities, and prototype parts is limited* Physical resources, such as hardware tools and parts libraries, are often beneficial when designing and testing prototypes. Specifically, product design engineers use physical parts as references, even when designing virtually, and a lack of access to these benchmarking tools is a challenge not yet discussed in the literature. Participant 5 describes this challenge:

> We have a benchmarking center where we have a lot of parts stored, and you can go and look at it. It's like a parts library, but cars are really big, so it's a whole building. Not having access to those kinds of internal resources has been more of a bottleneck than any external resources. (Participant 5)

Prototyping and testing are greatly impacted by the lack of access to physical resources. While engineering prototyping and testing traditionally happen within the same facility, the shift to virtual work has made access to components and testing facilities a significant challenge. Another illuminating example of this challenge from our interviews involved verifying the colour of prototype parts. As one participant describes: "Normally in the office, we have somebody … in charge of checking colours of printing and colours of product.… Because I don't necessarily have that experience or knowledge on how to evaluate it, I missed those types of things" (Participant 15).

We found that this challenge was brought up most often by those participants in non-management positions and those in small organizations. It was more likely that the team was previously co-located in small organizations, with easy access to all facilities; thus, the absence of parts and tools may be felt more strongly. We also found that the two participants we spoke to in the aerospace industry did not discuss challenges related to lack of physical access. This finding is likely a result of the classification of these organizations as exceptions to work-from-home mandates; these interviewees always had the option to access the organization's facilities if needed.

*Challenge 5: Opportunities to de-risk before pre-production sign-off are lost* Another common challenge that plagues many activities throughout the product design process is the reduction in feedback provided by other members during now-virtual design reviews. In this section, we specifically focus on late-stage design reviews, where teams would normally review the physical product together. Participants in high-risk industries, such as nuclear and aerospace, shared this challenge. Our interviewees found virtual design reviews less interactive and their peers less engaged. The difficulties of distributing sample components among team members, caused by cost constraints and intellectual property (IP) concerns, further reduce engineers' opportunities to identify issues. These challenges pose substantial risks during this phase, as any design flaws have the potential to

cause significant problems and downtime during production. The following quote illustrates this concern:

> Because I'm not sending [prototype parts] to anybody … [while] I can evaluate most of the specs because I'm familiar with the product, ... there are always things that other people will find that are not necessarily in the spec or that we haven't actually thought about before. (Participant 15)

Since prototypes can embody different meanings for various stakeholders (Lauff et al. 2020), it is beneficial for final prototypes to be widely shared during design reviews. Specifically, tactile interactions with prototypes are important when persuading executives, thus we might expect this challenge to hinder the ability to obtain final executive sign-off for products reviewed virtually. A hybrid working arrangement that requests in-person attendance for final design reviews may be a solution to this challenge.

In addition to receiving feedback from team members, it is also important to gather user feedback pre-production for products in certain industries. Participant 8 describes this challenge when conducting virtual user testing in the medical sector: "Especially when it comes to products that have a hardware component, it's really hard to simulate, or at least tell your users to imagine that they're holding a product and imagine that they're interacting with a patient." While remote user testing of software products is well studied, scholars note that extending this process to hardware products would require distributing prototypes to and collecting prototypes from users (Larsen et al. 2021), which creates additional challenges, as discussed above. However, a recent study shows that some organizations use this method and have reported time and cost savings (Cecchi et al. 2022). Virtual testing may not be deemed an acceptable alternative in industries requiring regulated testing.

*Challenge 6: Supervision of a dispersed production team is limited* With companies beginning to operate with fewer staff physically present simultaneously, supervisors are often unable to oversee production activities in person. Companies that would typically send staff to manufacturing facilities overseas to monitor production instead rely on more detailed reports from external staff. The absence of this specific challenge in the literature suggests that it may be a new challenge exacerbated by travel restrictions during the COVID-19 pandemic. However, our participants shared that it may be possible to supervise production remotely, reducing unnecessary travel in the future and thus controlling their costs and environmental footprint. Here, Participant 2 describes how they carried out their typical production process: "Normally what we would have done is we would have had two people at a time just slowly rotating out [of the country to the manufacturing plant] and actual engineers there teaching [the manufacturing staff] how to build the product."

The lack of physical supervision also resulted in information loss:

> If there's an engineering change to communicate across three different shifts in a day, [up to] four different shifts in a week when you're not allowed to interact with [production workers] face-to-face, that was hugely challenging. [It was easier when] you have those in-person meetings, and the whole shift would understand what's happening, what the priorities are. (Participant 9)

This challenge was described often by those in management positions and least often by those in large organizations. This finding may be caused by large organizations having dedicated production teams that could continue working in person during the work-from-home period. Understandably, those who worked in mass-production industries, such as consumer goods and manufacturing equipment, spoke most about this challenge.

*Strategy 3: adopting digital solutions for product reviews, sign-offs, and production supervision* Historically, many engineering organizations relied on physically marking up paper drawings and using physical signatures for final sign-offs, and they needed to transition to digital solutions while working virtually. Participant 10 shared their solution of transitioning from physically marking on printed drawings: "For redlining drawings, we'll now actually draw on the PDFs—like a red line—and put our PDF signature on it. [We're] trying to replicate the original procedure in [as] digital [a] way [as] possible."

With some product design engineers working virtually on a more permanent basis, fewer opportunities exist for them to meet face-to-face with technicians and discuss physical product testing results or issues. Some teams have adapted by having technicians share their test results through more detailed reports: "typically, we'll visit when our parts are in production and going through testing…. instead, I'm getting more detailed test reports from them than I typically would (Participant 18)." When unforeseen trouble arises, design engineers also rely on video calling and photo/video sharing with the technicians to help diagnose any concerns.

Participants also discussed automating data collection and information flows, such as real-time tracking of test parameters or product quality and displaying results on online dashboards, a noted strategy with a high potential to solve COVID-19-related manufacturing challenges (Agrawal et al. 2020; Hussain et al. 2021). This process improves the engineers' ability to evaluate performance continuously and frees up technicians to work on higher value tasks. One participant describes their process: "We're continuing to put more and more of our data electronically accessible….and then [making sure parts, measures, and tests] get automatically [uploaded and] charted (Participant 14)."

As an alternative to sending engineers to facilities overseas as they normally would, one organization set up high-quality cameras around the production lines to stream video continuously. Engineers at the head office would observe numerous sections of the production line via live video and provide feedback to the manufacturing staff. To address 24/7 production activities and time zone differences, some North American engineers would even adjust their working hours to monitor production lines and provide feedback during early morning hours. While this specific method of remote supervision has not been found in the literature, a recent Industry 4.0 report recognizes that digitization of the manufacturing process will allow for remote supervision (Agrawal et al. 2020). Participant 2 describes the Zoom setups implemented to monitor the production of complex products.

> We were able to set up … a bunch of really good camera setups around the lines. We were able to have multiple Zoom calls basically going on in parallel. We'd have a couple different rooms; one [is] maybe focusing on assembly issues, one might be focusing on calibration issues.…We are interested in seeing their hands and the tools that they're using to say, 'Oh, you're not using a torque driver' or, 'Oh, you didn't put Loctite on that.' (Participant 2)

While product design engineers were able to adopt digital solutions during the mandated work-from-home period, highly regulated industries may not be able to rely on these solutions long-term without changes to the regulations. Participant 8 explains: "if we were doing official, regulated testing of our devices at the final stage for regulatory submission, it would take some documentation to cover why we think [virtual user testing] is valid."

*Strategy 4: Leveraging rapid prototyping tools and employee ingenuity* The rise of rapid prototyping tools, such as 3D printers, sped up by the COVID-19 pandemic (Tareq et al. 2021), greatly improves the capacity to fabricate parts without traditional supply chain support (Camburn et al. 2017). In our sample, product design engineers explained that they could simply print any required parts at home instead of ordering them externally and waiting for delivery. One participant described buying a 3D printer for carrying out prototyping and testing tasks to great success:

> Initially, I did buy a [$400] 3D printer ... that was actually pretty good. I was able to prototype a lot of stuff…. I was able to do a whole bunch of [tests] just by printing in the garage … I would have spent $2,000 on 3D prints if I did it externally. (Participant 16)

One company took it a step further, and a Program Manager was able to select employees who could run "at home workshops" by "identify[ing] the best people who were multidisciplinary enough that they could get the most value out of having a [prototype] at their house (Participant 2)." The company "sent prototype units home with them so they could be the eyes and ears and help other people run tests with [their] unit at home (Participant 2)."

Although at-home prototyping is under-addressed in the literature, the legal implications of this are beginning to be investigated (Okonkwo and Adeniran 2021). One participant described working within the company's IP restrictions with some ingenuity, collecting parts to help their co-worker build a home test setup.

> Typically [the company] is very strict on IP and IP leaving the building, but there were some tests [my employee] wanted to do that didn't [risk sensitive IP], so he needed me to find a long clear tube … a fan, a power converter, and a few other parts.… I found the parts, [and] dropped them off, and he's got a wood-work shop in his garage, so he kind of just went at it. (Participant 11)

Additionally, some participants described their organization's process of shipping prototypes or parts ordered to designers' homes. For example, Participant 18 explains, "another thing that's happening with the prototypes that we get during Testing and Refinement phases, they're all getting mailed to my house…I have a lot of prototypes in my home that I typically would store at my desk at work."

Although this strategy is not industry-specific among our participants, not all products can safely be prototyped or assembled from home. For example, Participant 4 describes limitations to this strategy when developing manufacturing equipment: "we happen to be developing fairly big things…. we've been able to print some of the stuff…[but] we would need to build bigger things in the shop."

Some roles required participants to bring home a multitude of tools. Participant 12 explains, "another one of my responsibilities is I perform teardowns of devices… I'll broadcast them via [Microsoft] Teams video to an audience of 50 plus. So the tools are mainly used for things like that and also for analyzing hardware devices." The Project/Program Managers we spoke to brought up both proposed strategies: they implemented new digital tools and relied on dispersed rapid prototyping. These strategies were most often discussed by senior Technical employees and least often by Managers. Rapid prototyping tools were discussed largely by those in medium and large organizations, as they have more resources to send home with designers.

Although our participants devised creative strategies for working with hardware from home, certain engineering roles such as production line engineering or physical testing may have no virtual substitute and require in-person presence for the foreseeable future. Until advanced technology enables these tasks to be done remotely, there continues to be the

need to study virtual teams along the spectrum of virtuality and how best to employ hybrid in-person and virtual teams (Martins et al. 2004). Lakemond and Berggren (2006) stress that managers do not need to adopt an "all-or-nothing" attitude when deciding on a working arrangement; alternation of co-locating and dispersed teams may be a viable option. Despite the challenges presented, our participants demonstrated the possibility of continuing production while moving towards a more virtual and distributed work model.

## 4.4 Challenges and strategies for communication and project management

Communication and project management are two major themes that play a role in all phases of the product design process, which was echoed by our findings that every participant discussed at least one of the challenges listed below. Given that product design is a team endeavour, and a fundamentally social activity (Cecchi et al. 2022), effective communication is critical to success. Project management, which involves scheduling, coordinating, and facilitating many tasks within the product design process, is also crucial in ensuring that products are delivered within time, cost, and quality goals. Virtual work literature consistently discusses project management challenges, specifically virtual product design and engineering literature (McDonough et al. 2001; Chinowsky and Rojas 2002). In a virtual work environment, in-person interactions are no longer possible, transparency between team members is decreased, and coordination requires more time and effort (Morrison-Smith and Ruiz 2020). These qualities result in communication and project management being especially challenged virtually. As such, we expand upon some commonly reported virtual communication and project management challenges and identify potential strategies employed by participants below.

*Challenge 7: Difficulty accessing people and their work* Many interviewees reported challenges related to difficulties in accessing people and their work, a widespread and documented consequence of virtual knowledge work (Wang et al. 2021). This challenge was mentioned by 19 out of the 20 participants we interviewed. We found that participants who worked in large organizations cited this as a factor that impacted their ability to reach people, "you have to just not give up, it sounds kind of silly, but with such a big company, everyone has a lot of priorities…So sometimes you have to be the squeaky wheel" (Participant 5). Those in small organizations, that may have had a flatter structure before, found communication became more formal:

Before, at the meeting, we're all kind of on the same level in a sense, cause we're all there. We're all present. We're all discussing the same thing. Now I feel that the hierarchy of the company is a little more

important somehow. Like I don't feel as comfortable reaching out to say the head industrial designer, who's my boss's boss, and bringing up my concerns through a direct message. (Participant 7)

Many interviewees highlighted the significant decline in impromptu, informal interactions with colleagues during the shift to virtual work. Given the interdependent nature of tasks in the product design process, participants described that quick in-office informal interactions with team members, which were instrumental in sharing information, transferring knowledge, and seeking help, were harder to come by when forced to occur virtually. Previous virtual work literature reaches similar conclusions: communication frequency, particularly in terms of spontaneous interactions (Cecchi et al. 2022), decreases as team members become more dispersed (Leenders et al. 2003). Participant 6 describes this challenge: "I'm used to being in an open office environment…. and I'm used to having a team around me that I can always ask questions to and talk things out with and figure out how to approach different designs." The increased barrier to informal interactions negatively impacted productivity for some interviewees.

In addition to missing the informal interactions that help advance the participants' projects, many also missed chance encounters with other teams (projects or functions) in the office and hearing about new initiatives not directly related to their work. Research shows that siloed teams are a common challenge in firm-wide virtual work, resulting in fewer cross-group interactions (Yang et al. 2021). These conversations, sometimes known as incidental learning (Brown and Duguid 2000), could lead to cross-project learning, bringing diverse perspectives into the problem-solving process. One participant explained, "there is a … miss [of] the random conversations. Just finding out that, 'Oh, you're dealing with that problem….we had that problem three years ago… let me send you an important report on that.' The serendipitous interactions dropped down (Participant 11)." In response to this challenge, research has shown that personal updates about family members or weekend plans, which some interviewees reported being more common during virtual work, help replicate some of this spontaneous information sharing (Kraut et al. 2002). In addition to reduced knowledge sharing, participants reported feeling disconnected from the organization due to a lack of exposure to other company projects.

Furthermore, with engineers completing their work at home, they lose a mutual sense of progress with the lack of physical transparency. This loss can lead to challenges in project coordination. For example, Participant 13 reported the following:

Everybody's working at home, doing their own work on their own timeline….some people work faster than

others. Some people have a longer lead time than others. Some peoples' suppliers work differently than others. So, just keeping track of all of that has changed (Participant 13)

*Challenge 8: Shallow and inefficient communication*
Another significant challenge that participants reported was that the lack of non-verbal communication would reduce the quality of conversation during meetings. This could, in turn, lead to design decisions being made prematurely or without everyone being fully on board (Kniffin et al. 2021). Product design engineering is a social process that involves the rich exchange of information to generate new ideas, reach consensus, and collaboratively problem-solve. In a physical environment, participants would read facial expressions or body language to gauge reaction and comprehension from their teammates, but this non-verbal communication is often lost in virtual work. Participants can easily be distracted or bored in online meetings, especially while staring at names and avatars rather than seeing their colleagues' faces. This sentiment is emphasized by Participant 5, who struggled to gauge the opinions of her colleagues during meetings:

> I had a meeting where a manager had a really strong opinion that I couldn't tell if everybody else agreed with him or not.… That's kind of weird because normally, you can kind of look around and get a sense of [what] other people are thinking. (Participant 5)

This challenge was discussed mostly by those in regulated industries such as automotive, aerospace, and nuclear, and exclusively by those in large organizations. For example, Participant 4 explains the impact of the absence of body language in large meetings: "when you're all in the presence of everyone else, you kind of tell when someone wants to say something, sometimes that's a little trickier [online], especially large calls where there might be 50 people, 100 people."

In addition to the lack of visual cues, technology-mediated communication may also introduce accessibility barriers, further exacerbating poor communication. Technological accessibility is a productivity and equity imperative, and is particularly important in product design engineering, where a diverse team is crucial for innovation. With the shift to working in a virtual environment, some people may struggle to communicate effectively in meetings or calls. Participant 5 describes that accessibility solutions in meetings can help employees follow along during discussions, but were unfortunately often an afterthought during the switch to virtual work.

> Accessibility features like captions on meetings can be really helpful to people who are either deaf or [for people who] just learn better if there's text that they can follow along with. Or if they're speaking English

as a second language, having a caption [is] going to be really helpful, and that's not always available to everyone. (Participant 5)

Although only one participant mentioned accessibility challenges, it is still an extremely important factor to consider as we shift towards a hybrid model of working. Tang's in-depth study of the accessibility needs of virtual workers identifies a number of considerations that managers should be aware of, such as the expectation of video use or screen-sharing (Tang 2021).

*Challenge 9: Building rapport between teammates virtually is difficult* Project management involves integrating the inputs and outputs of many product design engineering teammates. Often, this requires requests that may be, in the eyes of the colleague, non-essential. A strong Project/Program Manager can rely on their interpersonal relationships and reputation to ensure that they promptly receive information from their colleagues, which is even more critical to project success when working virtually (Hoegl et al. 2007). However, in a virtual setting, it is harder to build rapport and convince teammates to put in the work required for project management, as described: "[If] you've never met someone before, it's harder to get people to understand that you're not just the name, sending emails to them. They're less likely to respond or less likely to attend your meeting (Participant 19)."

Building rapport was discussed by Project/Program Managers and Technical System Engineers in terms of finding it difficult to acquire needed information from individuals without a prior relationship. For example, Participant 5 explains, "because there are so many stakeholders in system-level projects… it's just hard to get everybody to give you the information that is needed to make a project decision and move on." Technical workers articulated this challenge in terms of building new relationships for employees who switched teams or were onboarded while working virtually. Recent COVID-19 virtual work literature found that while existing relationships were less impacted by virtual work, forging new relationships with colleagues or clients proved challenging (Cecchi et al. 2022). This challenge was discussed least often by Managers.

Relationships between team members are important for supporting designers in the search for novel solutions and sharing information in complex product developments (Cecchi et al. 2022). Scholars suggest communication strategies to help virtual teammates build rapport, such as holding in-person kick-off meetings or using video conferencing at the start of projects to build relationships and trust (Chinowsky and Rojas 2002; Lakemond and Berggren 2006; Stone et al. 2018; Lumseyfai et al. 2019; Cecchi et al. 2022). Although some participants spoke about the use of these trust-building strategies in our interviews, team processes take longer to

develop in virtual environments (Blanchard 2021), and we expect that the benefits of these strategies will become more clear over time.

In addition to the communication challenges described, participants also shared some of the benefits of virtual communication that managers should consider as the mandated virtual work period ends. Literature often cites the "level playing field" as a benefit of virtual work (Cecchi et al. 2022), and we heard this from our participants as well. They noted that virtual work allowed team discussions to be more inclusive; those in junior roles could offer their feedback comfortably, resulting in decisions being made in a more decentralized and democratized manner. Meetings also became more intentional as teams put more effort into connecting the right people with the right information, in contrast to typical large meetings filled with peripheral members. Interestingly, some of our participants even revealed that they were able to build closer connections with co-workers because of the more frequent and personal communication that resulted from working in their homes, as echoed in Cecchi et al. (2022). These personal connections can lead to networking, which has been shown to increase the number of resources involved in a design activity (Brisco et al. 2018).

16 out of the 20 participants we spoke to discussed the following communication and project management strategies. Most participants explained how their teams or organizations had created additional conversational opportunities during the work-from-home period, and nine discussed new project tracking tactics. All participants working in small organizations added more meetings while working virtually, and those in medium-sized organizations were more likely to add formal project tracking tactics.

*Strategy 5: Purposely creating more conversation opportunities (formally & informally)* To address the decline of impromptu interactions and the lack of physical transparency, most participants highlighted their use of redundant communication strategies to create additional opportunities for team members to connect. They reported introducing weekly check-in meetings, specifically for re-communicating important project-task-related information, which is a recommended strategy for virtual engineers (Lumseyfai et al. 2019), and was empirically demonstrated by product development managers during COVID-19 (Cecchi et al. 2022). Participant 9 elaborates, "it's helped to [have]…a scheduled weekly meeting other than the daily meeting, just to make sure that nothing is lost."

In addition, some interviewees also created small, topic-focused groups on messaging platforms or breakout rooms using video-conferencing software to address the lack of spontaneous conversation. More dialogue was encouraged by creating a dedicated space for 'water cooler' conversations to occur, which are critical for virtual work success

(Lumseyfai et al. 2019), improving rapport between teammates (Mcgloin et al. 2022), and fostering the transfer of tacit knowledge (Cecchi et al. 2022). In the quote below, Participant 5 describes the introduction of a bi-weekly tech club meeting at her company:

> [We have a] tech club for discussions about our process and our tools and things that weren't specific to a single project but were more relevant for the entire team. Those conversations used to happen on the edges of some of our engineering review meetings … the tech club makes a space for some of those conversations that we are already having but then stopped having once we went fully virtual. (Participant 5)

Another participant discussed how their team maximized the usage of the breakout room feature in virtual meetings to facilitate small group discussions:

> With Zoom, we actually started using their breakout room feature….someone would be like, 'Hey, I have a question.' I'm going to be like, 'okay, we're going to just tag you in a sidebar'…. And at the end of [the meeting], we'd be like, 'okay, you guys want to talk about this, and you guys want to talk about this.' And then that would kind of replace the water cooler and the post-meeting discussions. (Participant 2)

The unstructured conversation opportunities and dedicated topic conversations that our participants created are said to be crucial for virtual work innovation and learning (Lumseyfai et al. 2019). While our participants noted that these opportunities increased transparency and knowledge transfer, they might not benefit all roles equally. In fact, in other virtual work literature, managers had more meetings than non-managers (Cecchi et al. 2022) and found redundant communication overwhelming and blurred the lines between work and home (Dandalt 2022).

In terms of communication tools, we found that almost all participants used a combination of instant messaging-like software, email, and video-conferencing software (without using video, in some cases) throughout the product design process. Although their reliance on other design technology varied throughout the product design process, communication tools were used consistently across all design phases. As flexible working arrangements persist in the coming years, managers should carefully select appropriate communication tools and provide clear guidance on usage for each type of task or phase of the project to avoid overwhelming their staff. Existing work on Media Richness/Synchronicity Theory for technology suggests that teams should use asynchronous tools when conveying information and synchronous tools when converging on ideas and decisions (Maruping and Agarwal 2004; Dennis et al. 2008; Montoya et al. 2009). Novel tools such as Brisco et al.'s Computer

Supported Conceptual Design evaluation matrix can help leaders systematically identify gaps and select the right combination of technologies that will meet the requirements of their teams (Brisco et al. 2020).

While our paper highlights communication strategies established by the product design engineers we interviewed, we also note that these strategies could have both positive and negative effects, and their adoption must be approached with caution. Virtual meetings provide benefits such as allowing more members to participate simultaneously, increasing flexibility for participants, improving intra-team transparency, and even increasing the quality and quantity of ideas generated (Thompson 2021). However, some participants also reported reduced engagement and being overwhelmed with a barrage of meetings, consistent with other COVID-19 virtual work literature that shows the increase in unscheduled communication was greater for engineers than non-engineers (Yang et al. 2021). Further research can help teams identify a balance that allows for increased transparency without overwhelming schedules (Gibbs et al. 2021b).

*Strategy 6: Introducing new project tracking tactics* Participants introduced new project management tools as they shifted to virtual work to address project coordination challenges. For example, Participant 14's team started using a new shared project tracking software to improve the visibility of schedules and tasks within the team: "people can schedule their own tasks and see what's going on and see what connects….it's been really helpful for me to see what my team is working on and make sure that everyone's on the same page with the priorities." These virtual "collaboration boards" are a previously indicated key feature of the technology integration required for virtual engineering teams (Lumseyfai et al. 2019). Other participants found it useful for team members to share daily textual updates, perhaps an adaption of Scrum meetings used in Agile development (Highsmith 2001). Virtual project coordination proves to be challenging for product design engineering teams and requires new tools and strategies to balance scheduling and planning.

## 4.5 Current attitudes towards virtual work

Contrary to collective belief, the product design engineers we interviewed have shown that it is possible to develop new products while working almost entirely from their homes. While there is limited literature investigating these work-from-home models specifically in teams designing a physical product (Bellotti and Bly 1996; Lumseyfai et al. 2019), there is research informing virtual work in the context of a multinational organizations' need to coordinate co-located design teams spread across the globe (May and Carter 2001; Lakemond and Berggren 2006; Eppinger and Chitkara 2009; Montoya et al. 2009; Song and Song 2010). Adding physical parts into the product design process introduces complexity

and typically requires laboratories, large equipment, and in-person meetings—organizations have previously never needed to explore an alternative to working in proximity to these resources.

However, the COVID-19-imposed work-from-home regulations allowed organizations to re-evaluate the feasibility of virtual and distributed working, which they had previously dismissed. Almost every participant (19/20) realized how much of their work they could complete from home after working virtually for merely a few months: "A lot of work can be done remotely. I think that [COVID-19] just forced the decision for a lot of employers. And I think they realized that 'Hey, it's doable in a lot of cases' (Participant 16)." There are notable advantages of moving towards a more flexible future of work. Recent advances in technology, an increased commitment to reducing environmental impact, and better work-life balance expectations from new generations of workers will only push society faster towards a distributed working model (Global Workplace Analytics 2020b; Towers-Clark 2020). Thus, it is critical that we use this opportunity to improve on these existing challenges for distributed product design engineers, so that organizations can best prepare and become resilient to future shocks.

Participants who were part of large organizations were less shocked by the change, "I think people's work is becoming more remote, and part of the reason why we already had a lot of systems set up for people attending meetings remotely is because we are a global company (Participant 5)." Similarly, those participants in regulated industries already had processes in place that eased this transition, "we're required to electronically track whether you're working from home or at the office anyway…it's not too much of a workflow change to be remote and still have to document all of those things (Participant 8)."

Despite this realization, many of our participants also speculated that working exclusively from home might still be out of reach. Participant 12 describes:

> We absolutely have to have access to a test lab. [I] need certain machines and equipment to be able to do my job as a mechanical engineer. So I don't think that we'll ever be able to move entirely to a remote work model, but I do think that we can probably scale down at some point. (Participant 12)

Specifically, our participants described aspects of their roles that may lend themselves more easily to virtual work than others. Participant 4 explains this in terms of his Technical role:

> Maybe 90% of my job is computer work. And then there's that 10% where I need to have my hands on something. So I think always being onsite in the office doesn't always make sense…So that's why I

say 50/50….I think [that is] the best of both worlds, that's not going to be the same for every job, role, or every kind of company. But I think as far as [company] design engineering goes, I think that's a really good balance…having time set aside…[where] I'm working from home where I know I can just sit down for three hours straight and work on a CAD design, to me that's really important to have. (Participant 4)

Fewer distractions are a documented benefit of virtual work (Laumer and Maier 2021); our participants cited this as one reason they'd like to continue with a hybrid approach: for the parts of the product design process that require detailed individual work, such as CAD modelling or documentation, participants believe they are more effective in their distraction-free home environment.

However, not all product design engineers that we interviewed shared this opinion, "I knew that it wouldn't ever be a permanent long-term solution unless our design roles changed considerably, but at that point, you're just a CAD monkey instead of an actual engineer. So there's not much point in that (Participant 6)."

Most of the product design engineers that we spoke to specified that their ideal working arrangement would be a hybrid approach: allowing for the flexibility to go into the office when needed and the ability to work from home when they felt it would be more productive. Participant 9 describes his ideal weekly schedule:

I can totally see it being divided by like: I've got these three meetings; I'm going to come in on Wednesday and have these three meetings. And then, for the rest of the week, I'm doing my CAD work, which I don't need to interact with somebody…I think that will continue into the future because there's no reason not to. (Participant 9)

Concerning a hybrid approach, participants expressed worries that it would be inefficient to set up teleconferencing software for one or two team members working virtually: "I think there's kind of a critical mass there. I do believe that if there's still a minority amount of people working remotely, they won't be as effective (Participant 19)." Setting up the infrastructure and processes for virtual and distributed collaboration will only be worth the effort if a sufficient percentage of the team adopts the practice.

As evidenced by the wide range of experiences with virtual work demonstrated by our participants, individuals' attributes and organizational factors play a role in the perception of a virtual working style as well as its success in terms of creativity (Mulet et al. 2016; García-García et al. 2019) and productivity. Although it was not a focus of our study, virtual work inevitably compounds the line between personal and professional lives, and thus, we recommend,

based on other contemporary studies, that leaders tailor solutions to different personality types to help employees achieve work-life balance (Evans et al. 2021), with the likely outcome of improved employee morale, increased productivity, and sustained long-term engagement.

Though there is plenty of discussion about the effect of COVID-19 on knowledge workers in general (Wu and Chen 2020; Barbieri et al. 2021; Gibbs et al. 2021b; Kniffin et al. 2021; Laumer and Maier 2021; Madariaga et al. 2021), and studies which aim to explore impacts in specific industries (Brewin 2020; Pamidimukkala and Kermanshachi 2021; Škare et al. 2021), we could not find evidence in the previous studies to pinpoint the simple but challenging fact that we uncovered in our interviews: product design is a mix of Tangible and Intangible Design activities, and while is it possible to complete many Intangible Design activities remotely, it is near impossible to complete the Tangible Design activities from home. Managers should consider implementing tools that allow employees to replicate Tangible activities in the digital world and collaborate seamlessly from a distance. It is important to recognize how virtual work can impact communication, a key factor in product design engineering, and create explicit opportunities for casual conversations, cross-project learning, and rapid design feedback. Our participants have demonstrated the inventive strategies that emerge when managers embrace employee creativity when adapting to new situations.

### 4.6 Summary

As summarized in Table 2, our participants shared several challenges and strategies that they encountered in their virtual product design engineering work. Some of these challenges and strategies are referenced in previous virtual work literature more broadly, and some specifically in virtual product design or engineering literature, while others have newly emerged in response to the firm-wide and long-term virtual work period caused by the COVID-19 pandemic.

## 5 Limitations and future work

There are several limitations of this work that may affect the generalizability of the findings. A sample size of 20 is relatively small for virtual team interview work (Gibson and Gibbs 2006; Gibbs et al. 2021a); however, we worked to ensure that a wide variety of organization sizes, roles, and industries were represented, as shown in Table 1. We also conducted these interviews shortly after the government-imposed work-from-home restrictions to collect data before workers returned to the office. The sudden nature of this change may have brought about some of the findings reported in this work, and they may not be applicable for

**Table 2** Summary of challenges and strategies with referenced in the literature. Sources are only included in this table if they specify the challenge or strategy specifically in the context of virtual work

| Type of work | Finding | References in engineering or product design literature | References in broad virtual work literature |
|---|---|---|---|
| Intangible Design Activities | Challenge 1: Inadequate tools used for design knowledge representation and collaboration | May and Carter (2001), Wu et al. (2015), Jung et al. (2017), Anderson et al. (2022) | Colbert et al. (2016) |
| | Challenge 2: Slow design iteration and feedback | Bellotti and Bly (1996), Mascitelli (2000), May and Carter (2001) | Kniffin et al. (2021) |
| | Challenge 3: Individuals' sense of accountability is lessened | | Morrison-Smith and Ruiz (2020), Rober (2020) |
| Tangible Design Activities | Challenge 4: Access to physical tools, testing facilities, and prototype parts is limited | Velzen and Olechowski (2021) | |
| | Challenge 5: Opportunities to de-risk before pre-production sign-off are lost | | Larsen et al. (2021) |
| | Challenge 6: Supervision of a dispersed production team is limited | | |
| Communication and Project Management | Challenge 7: Difficulty accessing people and their work | Bellotti and Bly (1996), Leenders et al. (2003), Cecchi et al. (2022) | Morrison-Smith and Ruiz (2020), Wang et al. (2021), Yang et al. (2021) |
| | Challenge 8: Shallow and inefficient communication | | Karpova et al. (2009), Boland et al. (2021), Kniffin et al. (2021), Tang (2021) |
| | Challenge 9: Building rapport between teammates virtually is difficult | Chinowsky and Rojas (2002), Hoegl et al. (2007), Lumseyfai et al. (2019), Cecchi et al. (2022) | Morrison-Smith and Ruiz (2020), Blanchard (2021) |
| Intangible Design Activities | Strategy 1: Using new software or technology for sharing and collaborating | | |
| | Strategy 2: Using a model-based approach to develop systems | Ramos et al. (2012) | |
| Tangible Design Activities | Strategy 3: Adopting digital solutions for product reviews, sign-offs, and production supervision | | Agrawal et al. (2020), Hussain et al. (2021) |
| | Strategy 4: Leveraging rapid prototyping tools and employee ingenuity | Camburn et al. (2017), Cecchi et al. (2022) | |
| Communication and Project Management | Strategy 5: Purposely creating more conversation opportunities (formally & informally) | Cecchi et al. (2022) | Mcgloin et al. (2022) |
| | Strategy 6: Introducing new project tracking tactics | Chinowsky and Rojas (2002), Lumseyfai et al. (2019) | |

product design engineering teams making a planned decision to move to virtual work. However, as shown in Table 2, many of the challenges discussed adhere to themes present in pre-pandemic virtual work literature, which further supports the argument that these findings are valuable for product design engineering teams looking to transition to a more flexible work schedule in the future.

Additionally, as many of the participants interviewed continued to work virtually in the months (and years) following our interview, it is possible that organizations could have overcome some of the obstacles reported here. As addressed above, some of the overarching challenges uncovered in this study have been written about in virtual work literature dating as far back as 20 years ago and are still unresolved today. This study, therefore, expands on these persisting challenges and places them within the context of product design engineers.

Furthermore, this work examined the feasibility of virtual product design engineering work using activities in the product design process as a framework. However, many other

factors can influence the success of virtual work in product design engineering that we did not consider here. Our findings highlight how virtual communication challenges exist throughout all phases of the product design process; thus, it can be reasoned that studying other interpersonal processes in product design engineering would uncover new challenges and innovative strategies (Maruping and Agarwal 2004). In addition, we only looked at a macro-level model of the design process, summarized into a six-phase procedure. Wynn and Clarkson (2018) categorized different product design processes from the literature into three types: micro-level, meso-level, and macro-level, and each type provides unique insights and perspectives on the design process. Future work could include other models of the product design process. Finally, virtual product design engineering work can be evaluated for feasibility on the individual or team level to understand personal or team characteristics that are most conducive to virtual work.

Another limitation of this study is that all but one of our participants had been part of the same team prior to transitioning to virtual work; thus, we were unable to explore the consequences of building new teams virtually. Building trust and relationships in new, virtual teams presents additional challenges and is a richly researched topic (Cecchi et al. 2022). Researchers suggest prioritizing face-to-face meetings in newly formed teams whenever possible or alternatively using rich media like videoconferencing when in-person meetings are infeasible (Martins et al. 2004; Maruping and Agarwal 2004; Stone et al. 2018; Morrison-Smith and Ruiz 2020).

To test the generalizability of the findings presented in this work, we encourage others to survey product design engineers spanning a greater number of industries and organizations. The survey could test for the severity of commonly encountered challenges for product design engineers working from home as well as highlight the challenges that persist as teams mature in their new working style. We imagine that some of the challenges discussed here result from a lack of preparation: organizations were forced to shift to an almost entirely virtual model overnight. By employing a longitudinal research model, we can differentiate between these circumstantial challenges and those genuinely preventing product design engineers from adopting a more flexible working style.

## 6 Conclusion

Although long believed to be ineffective, we have shown that it is feasible for product design engineers to work in a distributed and virtual manner. Our study separated tasks within the product design process into Tangible, Intangible, and Communication and Project Management activities. We find that Tangible Design activities, which include physical tools, facilities, and products, are most challenging to complete virtually. Some of the challenges uncovered in this work are missing from existing virtual product design engineering literature. They include but are not limited to individuals' lessened sense of accountability, fewer de-risking opportunities before product sign-off, and limited supervision of production staff. We found that some tasks were even more productive in a virtual setting, while others, like physical prototyping and testing, may always require an in-person component. However, product design engineers have already started overcoming these challenges by adopting new model-sharing software tools, creating digital alternatives for engineering reviews and sign-offs, and leveraging rapid prototyping. The COVID-19 pandemic allowed product design engineers to realize the feasibility of virtual work, and here, we have provided an initial explanation of how this happened and what still needs to be done. While there still exists a need for some in-person work for product design engineers, we can see that it is possible for the industry to move towards a more flexible work schedule while remaining productive and effective. This shift will transform the role of a product design engineer as we know it, resulting in adaptive global teams that will, in turn, develop more innovative products.

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