Design Science

Front-end design prototyping strategies during remote stakeholder engagement

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Abstract

Engineers must engage project stakeholders effectively if stakeholder needs are to be met, and prototypes are key tools for communicating design form and function. Quality stakeholder engagement in the front end of design processes, in particular, is critical in the success or failure of design projects. As remote stakeholder engagement has become increasingly common as industry trends toward distributed design, there is a need to develop the theory and practices behind effective remote design processes, which have not yet been as well-studied as in-person design. This study explored the prototyping strategies for remote stakeholder engagement during front-end design used by 10 engineering practitioners and 10 senior engineering students through semi-structured interviews. Prototyping strategies were found to overlap with many of the strategies described by prior literature that are not specific to remote engagement modes, though several of these strategies were adapted to the remote context, and three emergent strategies for prototyping in remote engagements were identified. Designers' perceptions of remote versus in-person prototyping strategies for stakeholder engagement in front-end design, including perceived advantages and limitations, were also explored, and recommendations for educators to better prepare engineering students for hybrid and remote work are provided.

Keywords: Prototype, Stakeholder engagement, Remote design, Front-end design, Practitioner

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1. Introduction

Engineers must effectively engage project stakeholders to design effectively, and prototypes are a key tool for communicating design form and function to stakeholders (Viswanathan *et al.* 2014; Lauff *et al.* 2020) and identifying unknown aspects of design problems from stakeholders (Jensen, Elverum & Steinert 2017). Quality stakeholder engagement in the front-end of design processes, in particular, which according to Atman *et al.* (2007) includes activities like problem scoping, requirements definition and concept selection, is critical for the success or failure of design projects (Cooper 2019; Hansen & Özkil 2020). When engineers and stakeholders are not in the same physical location and engagement is conducted remotely, effective communication and engagement strategies may be especially important to overcome the absence of in-person communication (Asadi *et al.*

2017). Although remote engagements between designers and stakeholders create opportunities to share design information that would be difficult or impossible to exchange otherwise, remote engagements may also come with challenges of differences in language, cultural backgrounds or other aspects of designers' and stakeholders' contexts, further complicating communication (Deininger *et al.* 2019).

In addition, remote stakeholder engagement has become increasingly common, in part due to industry trends toward distributed design teams (Reimlinger *et al.* 2020); a trend which has accelerated due to the COVID-19 pandemic (Lund *et al.* 2020). Research has shown that early stage design phases can be among the most negatively affected by remote or distributed design collaboration (Asadi *et al.* 2017), however, and that both stakeholder engagement (Mohedas *et al.* 2020) and virtual prototyping (Deininger *et al.* 2019) are areas where engineering novices may struggle to be effective. In addition, traditional design guidance may become less relevant in new design contexts, such as remote design (Reimlinger *et al.* 2020).

Despite the increasing prevalence of remote design work, as well as the unique challenges of, and opportunities for, collaboration by distributed design teams and stakeholders, the theory and practices behind effective remote design processes have not yet been as well-studied as in-person design (Utriainen 2017; Reimlinger *et al.* 2020), especially during the design front-end (Asadi *et al.* 2017). While specific prototyping strategies used by practitioners during stakeholder engagements during the design front-end have been studied (e.g., Coulentianos *et al.* 2020*a*; Rodriguez-Calero *et al.* 2020), it is not known whether and how these practices apply to stakeholder engagement that takes place remotely. This research, therefore, investigated prototype usage in remote stakeholder engagement during front-end design activities across engineering designer experience levels.

2. Background

2.1. Prototyping practices and stakeholder engagement

According to Camburn *et al.* (2017), prototyping should be applied strategically and in a way that is appropriate for a given context. When prototypes are used without a particular purpose or strategy, resources dedicated to prototyping can be perceived as wasted (Lauff, Menold & Wood 2019). Moreover, inadequate prototyping and stakeholder engagement practices can ultimately lead to project failures if quality stakeholder input is not collected and incorporated effectively (Cooper 2019; Hansen & Özkil 2020). In addition, because prototypes can be used in a variety of contexts and have context-specific advantages and disadvantages, strategies for how to effectively use prototypes are needed for different use cases (Viswanathan *et al.* 2014).

Multiple tools have been proposed to guide the use of prototypes across design activities. For example, Dunlap *et al.* (2014) proposed a heuristics-based tool to support designers in developing prototyping strategies, Menold, Jablokow & Simpson (2017) developed a seven-part framework to support novice designers in developing prototyping strategies, and Jensen, Özkil & Mortensen (2016) summarized related strategies from a review of 81 studies on prototyping in engineering. Few tools are available specifically to support the use of prototypes

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for stakeholder engagement, however, where engineers must communicate effectively with a diverse range of stakeholders outside of the design team.

Viswanathan *et al.* (2014), Deininger *et al.* (2017, 2019), and others have called for improved curricula to help engineering students understand the value of, and strategies for, prototyping, especially in information-gathering design activities like stakeholder engagement. While engineering students have been found to use a variety of prototyping strategies, they may not be explicitly aware of the range of types of prototypes available (Lande & Leifer 2009). Similarly, Deininger *et al.* (2017) found that while novice designers' prototyping practices sometimes reflected recommendations found in literature, other prototyping skills were used infrequently and without intentionality in activities like stakeholder engagement.

2.2. Prototyping and stakeholder engagement strategies during front-end design

The front end of design is broadly defined as including background research, needs finding, problem scoping and definition, requirement elicitation, specifications development, concept generation, and concept development (Atman *et al.* 2007). Time spent in these stages of design is key to directing the rest of a design process in the right direction, and ultimately toward successful design outcomes. One part of front-end design is stakeholder engagement, for which prototypes are a necessary tool. The type of prototypes used, what questions are asked, and which stakeholders are engaged affect the information collected by designers (Deininger *et al.* 2019), and therefore affect design outcomes. Though prior research has established the importance of contextualized, intentional use of prototypes in front-end design, specific guidance for prototype usage is understudied (Deininger *et al.* 2019; Coulentianos *et al.* 2020*a*; Hansen & Özkil 2020).

Examples of relevant studies that characterized prototyping strategies for stakeholder engagement in front-end design include Coulentianos *et al.* (2020*a*, *b*), which explored prototyping behaviors of global health design practitioners working in low- and middle-income countries and identified the prototyping strategies used to engage and develop relationships with a wide range of stakeholders, as well as to bridge differences in culture and language. Jensen *et al.* (2017) mapped the use of prototypes across eight engineering design companies, finding that prototypes were especially useful early in the design process to uncover limitations and assumptions in designs. Similarly, an interview-based study identified 17 specific prototyping strategies used by engineering practitioners to engage stakeholders in front-end design (Rodriguez-Calero *et al.* 2020). Although some remote engagements were included, the engagements studied were primarily in-person and differences in the application of the strategies between remote and in-person contexts were not explicitly distinguished. While the study was based on medical device designers, it included details on how specific design contexts led to prototyping and engagement decisions with the goal of producing findings that are transferable to other design domains. The 17 strategies were further explored in another study focused on automotive and consumer product design in addition to medical device design, which demonstrated broad applicability in front-end design across industries (Rodríguez-Calero *et al.* 2023). Studies focused on remote design have proposed some strategies, such as video prototypes for engaging stakeholders remotely to communicate concepts (Bogdan *et al.* 2012)

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and to determine requirements (Brill, Schneider & Knauss 2010). The extent to which these or other strategies are used in practice remains unclear, however, as well as whether and to what extent the general or industry-specific prototyping strategies described in existing literature translate to other design contexts, including remote design work. In addition, there is evidence that design guidance established for one location can have a negative effect on design outcomes when applied in another location, as shown in a study of design frameworks shared by globally dispersed design teams (Reimlinger *et al.* 2020). Therefore, there is a need to explore the transferability of previously documented prototyping strategies for stakeholder engagement in front-end design, specifically in remote design contexts, as well as the prevalence of proposed or previously undescribed strategies tailored to remote design.

2.3. Remote design work

Remote engineering design work has been increasing in prevalence for decades, as have the number of tools meant to enable stakeholder engagements in remote contexts (Li & Qiu 2006). According to McKinsey & Co. (Lund *et al.* 2020), the COVID-19 pandemic has accelerated the rate at which the fraction of remote versus in-person work is increasing. This report further claimed that scientific and technical jobs, such as engineering, are likely to average 1–2 days per week of remote work, as about two-thirds of typical tasks in these professions can be done remotely with no productivity loss, a ratio that will continue to grow as practitioners and organizations gain expertise working remotely. Due to these trends, designers need to be prepared to work effectively in a remote context now more than ever (Lund *et al.* 2020). Stakeholder engagement, specifically, is increasingly taking place remotely or in hybrid (remote and in-person) modes (Sanders & Stappers 2008), as this approach offers unique opportunities to designers, such as access to previously inaccessible stakeholders and the sharing of complementary skills and perspectives amongst diverse designers and stakeholders (Asadi *et al.* 2017).

Remote design also presents challenges to designers, however. As technology enhances designers' abilities to collaborate across distance, designers need to be especially aware of potential communication issues that are amplified in remote interactions (Baek, Kim & Harimoto 2019). Studies have found that teams working remotely faced obstacles related to communication and motivation (Asadi *et al.* 2017), team decision-making (Utriainen 2017), and in assessing the knowledge and competencies of remote stakeholders (Larsson 2007). Similarly, a study of remote design technologies and methodologies by Li and Qiu (2006) found that designers must take information that may be implicit for in-person engagements and make it explicit to overcome communication barriers and to successfully engage remote stakeholders.

2.4. Tools and training for remote stakeholder engagements

Engineering education often lacks proper training in front-end design work, and thus students have been shown to struggle with front-end design activities. Students have been found to undervalue stakeholder engagements (Mohedas *et al.* 2020), fixate on the use of high-fidelity prototypes (Mathias *et al.* 2018), inadequately implement ethnography techniques (Mohedas, Daly & Sienko 2014),

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and are not likely to associate prototype development to quality of final design outcomes (Nelson & Menold 2020). These practices do not align with recommendations from the literature and result in superficial design outcomes. The gaps between student behavior and the practices recommended for front-end design highlight the need for improvements to engineering education (Mohedas *et al.* 2014). There is also a lack of educational support for engineering students regarding remote design. Students have been shown to have more difficulty with remote design than in-person design, and therefore need coaching and materials to be successful in that context (Utriainen 2017). Explicit, advanced preparation can help students overcome the challenges of remote design quicker and make better use of prescriptive design guidance (Asadi *et al.* 2017). New design education strategies and materials that incorporate the realities of remote design work are needed so that novice engineers can be effective in modern, globalizing design environments (Reimlinger *et al.* 2020).

3. Methods

To explore ways in which designers employ prototyping strategies during remote stakeholder engagements, we used semi-structured interviews to characterize the strategies and perceptions of practitioner and student participants. This research was guided by the following research questions:

1. During front-end design activities, what prototyping approaches do engineering practitioners and students use to engage stakeholders remotely?
2. How do engineering practitioners' and students' remote stakeholder engagement approaches with prototypes compare to their in-person stakeholder engagements with prototypes during front-end design?
3. What outcomes do engineering students and practitioners perceive when using remote prototyping and stakeholder engagement strategies compared to in-person strategies during front-end design activities?

3.1. Participants

Interviews with 10 engineering design practitioners and 10 mechanical engineering students were conducted in 2020 and 2021. A sample size of 20 was set based on recommendations for qualitative, interview-based research (Hennink & Kaiser 2022). Similar sample sizes have been used in related, interview-based studies of stakeholder engagement strategies (e.g., Rodriguez-Calero *et al.* 2020, 2023). As this study was conducted during the COVID-19 pandemic, all interviews were conducted virtually by video call.

Design practitioners and students were included to support the diversity of engineering contexts included in our sample. There is no published set of recommended practices for remote stakeholder engagement, nor is it clear who, if anyone, may be considered an expert on remote stakeholder engagement since the frequency of remote design practices has changed rapidly in recent decades, as have the digital communication and prototyping tools (Li & Qiu 2006; Lund *et al.* 2020). Therefore, the inclusion of participants with a range of ages, experience levels, and design contexts was prioritized. Our second goal in including students and practitioners was to assess differences between student and practitioner

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Table 1. Practitioner participant demographics

Participant ID	Gender	Age	Job title	Industry	Years of professional design experience
Practitioner 1	Male	30	Mechanical design consultant	Consumer product design (internationally-based)	8
Practitioner 2	Male	26	Mechanical design engineer	Consumer product design (internationally-based)	3
Practitioner 3	Male	30	Senior mechanical engineering technical lead	Consumer product design (US-based)	7
Practitioner 4	Female	26	Senior engineer	Medical device design	3
Practitioner 5	Female	34	Mechanical engineering technical lead	Consumer product design (US-based)	12
Practitioner 6	Male	39	R&D director	Consumer product design (US-based)	18
Practitioner 7	Male	27	Design engineer	Automotive design	7
Practitioner 8	Male	26	Mechanical engineer	Automotive design	5
Practitioner 9	Female	24	Electrical R&D engineer	Automotive design	3
Practitioner 10	Male	32	Technical manager	Consumer product design (internationally-based)	3

strategies with possible implications for the improvement of engineering education or practice.

The 10 engineering design practitioners recruited had at least 3 years of relevant work experience and were employed in the design of medical devices, consumer products, or automotive design. All participants had transitioned to partial or fully remote design work due to the COVID-19 pandemic. Descriptions of practitioner participants are shown in Table 1.

The 10 student participants were seniors in a mechanical engineering program in a large Midwestern university in the United States. Graduating seniors were selected to allow us to identify the strategies of engineering students at the end of their education who were about to enter the workforce. Student participants were interviewed during the month after the completion of a team-based, semester-long capstone design project course, which had been taught virtually due to the pandemic. The course required remote engagement with industry, academic, and/or community project sponsors. All student participants had some prior

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experience with in-person stakeholder engagements through previous design and manufacturing classes, and some had additional experience from co-curricular or other design projects. Of the student participants, six identified as male, three identified as female, and one declined to name a gender identity. As the ages and levels of design experience held by student participants were relatively similar compared to the ages and levels of practitioner participants, who represented a wider range of work experience levels and design industries, more detailed descriptions of student participants' design experiences are not shown.

3.2. Data collection

A semi-structured interview protocol was used to characterize remote prototyping practices, as this method is well-suited to the exploratory nature of this research (Creswell & Poth 2016). The protocol emphasized open-ended questions and was developed through the generation of subquestions related to our primary research questions. The protocol was also modeled on a similar protocol used in prior research on general strategies for stakeholder engagements with prototypes (Rodriguez-Calero *et al.* 2020), which did not control for whether engagements were in-person or remote. As qualitative research excels at developing transferable findings through in-depth analysis and rich description (Patton 2015), our approach aimed to describe specific practices and attitudes of participants in ways that may be transferable to a range of design contexts, but without claiming generalizability across all engineering design applications.

The protocol was piloted with one representative design practitioner participant and two graduate student participants with subject matter expertise before data were collected from research participants. The content and organization of the protocol were iteratively refined after each pilot interview, resulting in an interview guide containing the questions used in data collection, as well as prompts for the interviewer to support follow-up questions.

Practitioners and students were asked the same questions, although question language was adjusted to professional or educational project contexts. For the first half of the interview, participants were asked questions about a specific design project that they selected in order to ground and give context to their responses. Broader, reflective questions were asked during the second portion of the interview to elicit general impressions of remote engagements with stakeholders beyond the selected project. Example questions asked based on specific design projects included:

1. Could you describe the prototype or prototypes you used?
2. What formats did you use to communicate with stakeholders remotely with prototypes? Why did you choose these format(s)?
3. How did you choose which prototype(s) to use with which remote format?
4. Did you use different prototypes for different stakeholders? If so, why?
5. Did you use different communication formats for different stakeholders? If so, why?

Examples of broader, reflective questions included:

1. Could you describe how, across your experiences, the types of prototypes you use for front-end engagements with stakeholders differ between remote and in-person engagements?

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2. Have you developed or do you use any specific strategies to make remote interactions more effective?
3. What are the main advantages of using prototypes to engage stakeholders remotely versus in person during front-end design activities, and why do you feel this way?
4. What are the main disadvantages of using prototypes to engage stakeholders remotely versus in person during front-end design activities, and why do you feel this way?

3.3. Data analysis

Interview recordings were transcribed and deidentified. Data were first analyzed deductively by two study team members (the first and second authors) to identify strategies for remote stakeholder engagements with prototypes during front-end design using a list of strategies documented by Rodriguez-Calero *et al.* (2020). Excerpts from interviews were tagged using this existing list of strategies to identify the approaches our participants were using in their remote work. To improve reliability, both researchers applied codes to a subset of three student participant transcripts and three practitioner participant transcripts and discussed discrepancies in coding until consensus was reached.

Then, using an inductive approach, which is defined by Creswell & Poth (2016) as the development of emergent patterns of meaning from the "ground up" rather than from an existing theory, and allowing for iteration in the development of patterns, as is recommended by Patton (2015), we analyzed the data for strategies distinct to remote, front-end design contexts. We defined these strategies based on how our participants described their usage in their projects. We also used an inductive, iterative approach to identify participants' perceptions of the relative quality and outcomes of remote and in-person prototyping strategies for stakeholder engagement during front-end design. To support reliability, three student and three practitioner transcripts were again first analyzed by the first and second authors to define strategies and perceived outcomes and ensure comparable analysis practices before continuing with the remaining transcripts. Codes were co-developed until agreed upon by each researcher, and all discrepancies between the coding of specific excerpts from transcripts were discussed until a consensus was reached.

To further support reliability, the academic, industry and educational experiences of the research team were leveraged to match our professional positionalities and expertise to research tasks. The first author has professional design experience in the US and internationally, as well as remote design experience before and during the pandemic. The second author had experience as a participant in the same capstone design project course as the student participants and was enrolled while the course was taught remotely due to COVID-19. Therefore, the first author led the initial coding of data from practitioner participants and the second author led the initial coding of student participant data. To avoid oversights or biases due to familiarity with participants' experiences, both authors then reviewed the other's work to provide a second, outside perspective to the data, and both authors then contributed to the full coding of all data. All members of the research team contributed to the iterative development of strategies and themes.

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In all cases, prototyping strategies were only coded when reported explicitly by participants, in the context of remote stakeholder engagements during front-end design, and with evidence of intent, meaning that the strategy was applied with evidence of forethought and to achieve a specific goal in an engagement with a stakeholder. Cases where prototypes were only used internally within an engineering design team were excluded, as evidence of strategies comparable to those used with other stakeholders who were less familiar with the details of a design was lacking. To remove the ambiguity that would have likely been caused by attempts to discern and count the frequency of codes within individual transcripts, whole transcripts were used as the unit of analysis for strategies, meaning we counted only the presence or absence of codes within each transcript. In addition, as many prototyping and remote stakeholder engagements relate to more than one of the strategies developed by Rodriguez-Calero *et al.* (2020), we reported the most closely related strategies with clear evidence of intent, rather than all strategies that may be relevant to a stakeholder engagement.

4. Findings

Our data showed meaningful overlap between the general prototyping and stakeholder engagement practices described in prior literature, as well as clear distinctions between the two modes of engagement. We also found consistent differences between practitioner and student participants in terms of the variety and intentionality of strategy usage, as well as perceptions of the effectiveness of remote stakeholder engagement. We consider the limitations of students' strategies and perceptions and the differences between students and practitioners as findings in and of themselves with potential implications for education.

4.1. Remote prototyping and engagement strategies

4.1.1. Use and adaptation of general strategies for stakeholder engagements with prototypes

Of the 17 general strategies for engaging stakeholders with prototypes described by Rodriguez-Calero *et al.* (2020), 12 were reported by practitioner participants during remote stakeholder engagements, 7 of which were reported by multiple participants. Table 2 includes a list of all 17 strategies from Rodriguez-Calero *et al.* (2020) and the number of practitioners and students in our study who described using each prototyping strategy in their remote engagements with stakeholders.

Of the 12 strategies described by Rodriguez-Calero *et al.* (2020) that were reported by practitioners in this study, two strategies were described by practitioner participants as being used for different purposes than were described for in-person engagements in prior research. In the case of the strategy "Show the stakeholder supplemental materials related to the concept to complement the prototype," practitioners reported the use of complementary prototypes to elaborate on design details. For participants in our study, complementary prototype formats were instead used to compensate for missing tactile feedback and/or in-person facilitation of an engagement by the designer. For example, Practitioner Participant 1 described sending physical mockup prototypes alongside Computer-Aided Design (CAD) models of a new product to potential clients:

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Table 2. Number of participants who reported strategies from Rodriguez-Calero *et al.* (2020)

	Strategy	Practitioner count (out of 10)	Student count (out of 10)
1	Show a single prototype to the stakeholder	10	10[a]
2	Brief the stakeholder about the project and the prototype(s) shown	7	10[a]
3	Show the stakeholder multiple prototypes concurrently	6	9[a]
4	Polish the prototype(s) shown to the stakeholder	6	3
5	Prompt the stakeholder to select prototypes and prototype features	4	9[a]
6	Show the stakeholder supplemental materials related to the concept to complement the prototype	4	3
7	Have the stakeholder interact with the prototype(s) in a simulated use case	3	0
8	Lessen a prototype's refinement when showing it to the stakeholder	1	1
9	Modify the prototype(s) in real-time while engaging the stakeholder	1	1
10	Present a deliberate subset of prototypes to the stakeholder	1	0
11	Observe the stakeholder interacting with the prototype(s)	1	0
12	Encourage the stakeholder to envision use cases while interacting with the prototype(s)	1	1
13	Task the stakeholder with creating or changing the prototype(s)	0	0
14	Reveal only relevant information to the stakeholder specific to the prototype or its use	0	0
15	Introduce the prototype(s) to the stakeholder in the use environment	0	0
16	Standardize the refinement of prototypes shown concurrently to the stakeholder	0	0
17	Make prototype extremes to show the stakeholder	0	0

[a]Strategies frequently used by students with limited, course-focused design goals.

> This combination between [sending] a physical product, which is an 80% representation of the product. and a CAD model which is also kind of an 80% representation because you can't feel how heavy it is and those kinds of things – I think we're able to convey our message better.

Similarly, the strategy "Polish the prototype(s) shown to the stakeholder" was described in prior work as a way to prevent stakeholders from becoming distracted by the unfinished details of a prototype (Rodriguez-Calero *et al.* 2020). In the remote engagements described by participants in our study, the level of refinement of a prototype was sometimes increased to offset a perceived risk of

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misunderstanding due to remote communication formats. As an example, Practitioner Participant 5 discussed sharing photos and videos of physical prototypes with clients:

> I'd spend some more time curating how it's presented. So, I spend a lot of time showing how the mechanism works, doing different trials, taking videos, and those are super helpful.

Student participants reported the use of nine of the strategies defined by Rodriguez-Calero *et al.* (2020), all of which were also reported by practitioners with the exclusion of "Present a deliberate subset of prototypes to the stakeholder," "Observe the stakeholder interacting with the prototype(s)," and "Encourage the stakeholder to envision use cases while interacting with the prototype(s)." Several of the strategies most frequently used by student participants were often used in ways that were tailored toward the meeting requirements of their course and limited in scope compared to practitioners' usage. Combinations of the strategies "Show a single prototype to the stakeholder" and "Brief the stakeholder about the project and the prototype(s) shown" were often used in a reporting format to demonstrate progress to project sponsor or instructor stakeholders or request design input in an open-ended way. For example:

> We would present a CAD model or picture of the physical prototype [to project sponsors]. And the purpose of having those prototypes is, one, to fulfill the requirement of the course, because that's required – we want to report our progress – and second is to get feedback on how we can improve on our solutions. (Student Participant 4)

Similarly, "Show the stakeholder multiple prototypes concurrently" and "Prompt the stakeholder to select prototypes and prototype features" were often used to prompt stakeholders to help the student teams make design decisions. For example:

> By showing our current [sketched conceptual prototypes], all of our [project sponsor and instructor stakeholders] realized that it is best just to focus on [one of our design concept options]. (Student Participant 8)

Outside of these four prototyping and stakeholder engagement strategies (numbers 1, 2, 3 and 5 in Table 2), practitioners participants reported an average of 1.8 additional strategies, each, while student participants reported an average of 0.9 additional strategies.

4.1.2. *Strategies specific to remote stakeholder engagements with prototypes*

Three distinct, previously unreported prototyping strategies for remote stakeholder engagement during front-end design emerged from our analysis. Each strategy is based on a specific way to communicate with stakeholders across distance, while allowing for flexibility in the types of prototypes used and the ways in which stakeholders were asked to interact with the prototypes. These strategies are described in Table 3 with the number of participants who described the strategy and an example excerpt from their interview responses.

In some cases, participants described these remote strategies as being used before the COVID-19 pandemic and/or in tandem with in-person strategies, while

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Table 3. Characterization and usage frequency of previously unnamed strategies for remote stakeholder engagement with prototypes

Strategy	Description	Practitioner count (out of 10)	Student count (out of 10)	Representative quotations
Present prototype(s) to the stakeholder through a virtual platform	Share a digital or physical prototype with the stakeholder for an engagement session conducted via a video call	5	7	"One of the particular things that helped in this project was that when we're at the early stages of conceptual design was doing some drawings on [an] online platform – it's like AutoCAD. And then sharing the drawings with the rest of the team and also with our clients." (Practitioner Participant 10)
Send physical prototype(s) to the stakeholder	Allow the stakeholder to interact with the physical prototype with or without guiding questions or instructions, but without the designer physically present	5	1	"We've developed a process that sort of works [for remote stakeholder engagement] and clients seem to be pretty engaged with getting physical [3D printed] prototypes and things to play with." (Practitioner Participant 3)
Present prototype(s) to the stakeholder through a third party instead of by a design team member	Facilitate interaction between the stakeholder and prototype through an in-person meeting with a third party who is not a member of the design team	2	0	"For the one project, they'll have the copy because we'll mail [a functional prototype] to their sales rep and then the sales rep will bring the prototypes to [a representative user]. And those two will be in person and we'll be remote [during the engagement]." (Practitioner Participant 4)

in other cases they described remote strategies as adaptations that were initiated or used more commonly during the pandemic.

4.1.3. Practitioner use of concurrent, complementary remote and in-person strategies

While distinct from general prototyping and stakeholder engagement strategies described by Rodriguez-Calero *et al.* (2020), the remote strategies listed in Table 3 were generally reported as complements to, rather than replacements for, other

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strategies by practitioners. For example, Practitioner Participant 3 described coupling remote strategy "Send physical prototype(s) to the stakeholder" with the strategies resembling "Prompt the stakeholder to select prototypes and prototype features" and "Polish the prototype(s) shown to the stakeholder":

> We produced some 3D printed prototypes that were painted and sort of "looks-like" models of just small sections [of the product]. [Clients] weren't present for meetings, so we just shipped them over to them and were like, "Give us feedback. Which do you prefer?" and gave them a specific list of questions of things we wanted them to answer. That was pretty successful.

Similarly, elaborating on the excerpt in Table 3, Practitioner Participant 4 described using the remote strategy "Present prototype(s) to the stakeholder through a third party instead of a design team member" along with the general strategy "Have the stakeholder interact with the prototype(s) in a simulated use case" in order to maximize the quality of remote engagements:

> We've been mailing [functional prototypes] to our sales reps and then the sales rep will take the kit and meet with the [representative user]. We set up a video call and we'll watch. We'll have them arrange their camera such that we can watch the [representative user] actually apply the product. And then we have a series of questions to ask.

As another example, Practitioner Participant 7 described combining the remote strategy "Send the prototype to the stakeholder for asynchronous interaction" with "Task the stakeholder with creating or changing the prototype(s)":

> [Manufacturing stakeholders] had the physical build with them there. So, if we had to do any design changes, they would actually take me through them on a video call while they were standing with the [functional] prototypes and I was at home.

Of the three new strategies specific to remote stakeholder engagement with prototypes described by practitioners, two were also described by student participants – "Present prototype(s) to the stakeholder through a virtual platform" and "Send the physical prototype to the stakeholder" – while "Present prototype(s) to the stakeholder through a third party instead of a design team member" was not reported.

4.1.4. *Student competencies in virtual communication*

Student participants' discussions of virtual communication strategies in remote engagements demonstrated considerably more depth and intentionality than discussions of remote prototyping and engagement strategies more generally. For example, Student Participant 6 reflected on the nuanced communication advantages of remote engagement strategies:

> You have a little bit more permanence [with remote engagements]. If you have a drawing and you send it remotely or you're presenting and then you follow up with an email afterwards with that drawing or that CAD file, that's definitely good in terms of the [project sponsor or instructor] being able to refer back to it.

Similarly, Student Participant 9 provided an example of tailoring the content and mode of communication to a stakeholder's needs in a virtual setting:

> [I was] more organized about [remote engagements with a project sponsor or instructor]. I'd have a game plan about what information I want to communicate

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> first then figure out the best way of communicating. I think slideshows come up more often when presenting to people outside of my immediate design team just because there's only so much you can talk about in a certain amount of time. So you have to hit every important point at a high enough level that they understand, but not so deep that you have to talk about it for five years. (Student 9)

In another example, Student Participant 2 described strategic intent in the communication strategy used when presenting virtual prototypes over a video call:

> With CAD we tried really hard to get nice [rendered images]. We specifically oriented our joint in a certain way and then added other graphics around to help visualize how exactly everything moves in relation to everything else, which I think made a big difference in letting our [project sponsor or instructor] understand exactly what we were talking about. In the middle of the presentation, it's difficult to have actual Solid Works up to rotate so we came up with a couple of methods just to make that process easier [which were tailored to] our specific solution.

4.1.5. Relationships between types of stakeholders, prototypes and remote engagement strategies

Across our findings, practitioners and students discussed various types of prototypes and stakeholders in relation to remote engagement strategies. While did not aim to assess relationships between individual strategies, stakeholders and prototypes in detail with the sample size and research methods used in this study, evidence of general trends was visible. Practitioner and student participants reported strategies like "Polish the prototype(s) shown to the stakeholder" and the use of higher-fidelity prototypes for nontechnical and management stakeholders who were less familiar with the details of a design to reduce miscommunication during remote engagements, as was discussed by Practitioner Participant 3:

> If it's a more senior stakeholder that is less technical [in a remote engagement] we'll have made sure [the prototype is] more polished to start with, and we'll just give [the non-technical, decision-maker stakeholder] shorter, simpler instructions.

Similarly, when discussing presentations to a project sponsor, Student Participant 4 described the use of more virtual prototypes for the sake of achieving clear communication.

> We don't use any [test material prototype] mock-ups when we're [presenting to our project sponsor virtually]. Instead, we use [digital] sketches or 3D models or something similar that is easy to present virtually.

As another example, Practitioner Participant 2 offered advice on how to adjust prototype fidelity based on the stakeholder in the context of remote engagements:

> The first thing is understanding who your stakeholder is. If it's somebody that you have good rapport with and understands how you communicate, then you don't need to take that prototype to the same degree of completion as you would if you're communicating with a potential user or with a key decision-making stakeholder like a manager […]. Remote work exacerbates those problems [related to communicating prototypes to stakeholders]. (Practitioner Participant 2)

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4.2. Perceptions of remote stakeholder engagement and prototyping

4.2.1. Perceived advantages and limitations of remote stakeholder engagement compared to in-person engagements

Practitioner participants reported a range of advantages and limitations of remote stakeholder engagements with prototypes compared to in-person engagements. Discussions related to the effectiveness of remote engagements, the broader impacts of remote engagements on design processes, as well as the quality designers' personal experience or satisfaction in their work. Perceived advantages and limitations are described in detail in Tables 4 and 5, respectively.

Compared to practitioner participants, student participants reported relatively few perceived advantages and disadvantages of remote engagements with prototypes versus in-person. In addition, student participants did not discuss intentionally balancing the advantages and limitations of prototyping strategies for remote stakeholder engagement during front-end design in most of the ways that were described by practitioner participants. Most student participants discussed cases of leveraging remote communication strategies into advantages, however. For example, Student Participant 1 reported that when sharing prototypes on a video call:

> I think it's more conducive [when you are] virtual in terms of hearing everybody. I feel like when you're in person it's a lot easier to talk over people. It's a lot easier to interrupt people. Whereas when you're virtual usually one person's talking…

Similarly, Student Participant 2 said that:

> I think it's nice that when you're remote – everybody instantly has a computer in front of them […] so all you have to do is hit share screen on your CAD and […] everybody's seeing exactly what you're seeing and there's no need to all crowd around one big TV screen.

In both examples, student participants demonstrated the ability to take advantage of specific strengths of remote communication formats while engaging stakeholders with prototypes.

4.2.2. Perceived impact of remote stakeholder engagement with prototypes on design

While many practitioner participants reported that remote stakeholder engagements during front-end design required more effort or advance preparation, all 10 reported that overall, they felt the use of prototypes during remote stakeholder engagements did not affect the final quality of design outcomes compared to in-person engagements. For example, Practitioner Participant 4 said that:

> In-person versus virtually, we weigh them the same.

Similarly, Practitioner Participant 3 reported:

> I think both ways [in-person and remote] get similar responses. Maybe over a different timeline. But in terms of the final outcome, I think it tends to be pretty similar.

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Table 4. Practitioner participants' perceived advantages of remote stakeholder engagement with prototypes

Theme	Subtheme	Number of practitioners who reported theme	Representative quotations
Effectiveness of stakeholder engagements	Remote stakeholder engagement can, in some cases, accelerate design processes	3	"I would say remotely you might be able to iterate faster possibly […] reach out to more people at the same time. So, if I would have a digital [CAD prototype], I have a list of people I want to share it with, I just have to change a few things. Just looking at having the physical prototype, we have a few different versions for different clients, but the time which has been invested in making those compared to changing the CAD model […] is significantly more." (Practitioner Participant 1)
	Remote engagement allows for access to otherwise inaccessible stakeholders	2	"The advantage here is that specifically we're getting that international feedback [from representative users by sharing CAD-generated 2D and 3D images]. We probably wouldn't have gone to all these different countries in person. We would have just gotten US feedback, and the product has different uses in the US versus internationally. So having the chance to do that virtually [due to COVID-19] is allowing us to get a wider range of feedback." (Practitioner Participant 4)
	Asynchronous remote interaction with prototypes gives stakeholders more time to create informed opinions about prototypes, which is not possible during typical in-person engagements	1	"[Asynchronous engagement] gives [clients] a longer period of time to engage with the prototype. So, typically, if it's in-person, they'll have [a functional prototype] for a few minutes in the meeting before you expect answers from them. Whereas remotely, you can send it and they may have it for a few days, and they share it round to all the different people who have views and are stakeholders but maybe wouldn't have got invited to the meeting that we would have been having the discussion in. So, it probably reaches more stakeholders and gives them a longer period of time to actually work out what it is that they like or dislike about it." (Practitioner Participant 3)
	Remote stakeholder engagement can, in	5	"I personally like it when I'm sitting at the comfort of my home, my desk, getting my

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Table 4. Continued

Theme	Subtheme	Number of practitioners who reported theme	Representative quotations
Design process efficiency and	some cases, allow for more efficient use of time and resources		coffee, and then thinking about the concept of the prototype, as opposed to being in the office with everyone running different tasks around me, noise level's high. I need to think about: 'Okay, I need to get on the train at 5:00 otherwise I'm going to be stuck in this traffic, or miss the next train and arrive 30 minutes later at home.' Just reducing those stresses helps a lot with the design or thought process or being focused […] in my opinion." (Practitioner Participant 10)
	Remote stakeholder engagement encourages more effective planning, communication, and creative problem-solving	5	"[Through remote prototyping I re-focused on] the get it right, 'measure twice, cut once' sort of thing. It forces you to think more about how things are going to come together when you're not the person that's assembling it. I think that probably would be good to apply that in any prototyping setting, regardless of whether or not you're in-person." (Practitioner Participant 2)

Practitioners instead described balancing remote and in-person strategies for stakeholder engagement with prototypes before and during the pandemic. As an example, Practitioner Participant 6 reported:

> Remote communication [with stakeholders] before COVID existed because we are a global company, and many of the senior leadership stakeholders reside in other locations and countries. Because of this, the process pre- and post-COVID largely remained the same. The teams go through decision stages early on with digital concepts because you can get broader variation without spending a lot of time fully realizing physical samples. Physical prototypes come later when there is more certainty on the end look and feel. In those cases, leadership would often travel on-site or are sent samples ahead of meetings.

In addition, the transition to increased remote work during the COVID-19 pandemic was discussed as a driver of innovation in remote prototyping and stakeholder engagement strategies. Multiple practitioners described finding new, low-resource means of prototyping and engaging with stakeholders while working from home that were effective but would not have been considered before the pandemic. It should be noted that even in cases where strategies were developed ad hoc during the pandemic, practitioner participants did not describe negative impacts on the overall quality of their work. For example, Practitioner Participant

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Table 5. Practitioner participants' perceived limitations of remote stakeholder engagement with prototypes

Theme	Subtheme	Number of practitioners who reported theme	Representative quotations
Effectiveness of stakeholder engagements	Remote engagements sometimes offer limited physical interaction with prototypes by stakeholders	3	"If it's got tactile feedback or somebody had been asking about, 'How do you think this feels?', that we can't do remotely." (Practitioner Participant 3)
	Remote engagements require increased planning and preparation	3	"The get it right, measure twice, cut once sort of thing. It forces you to think more about how things are going to come together when you're not the person that's assembling it." (Practitioner Participant 2)
	Remote engagements offer limited opportunities for designers to guide engagements or for stakeholders to provide feedback	2	"With the feedback that we got on the [functional prototype] where our [representative user] was saying, 'This is too much force required,' and he just wasn't happy with the performance. We don't know how hard he was actually pressing. Maybe he just wasn't giving it enough force at all and that's why it didn't really [work]. We weren't there in person to see what was happening. All we saw was what he was doing [over a virtual meeting platform] and then his thoughts about it after. So, it would have been easier if, had we been there, to say, 'Wait, put a little bit more pressure' or something like that, but that's just something that we'll have to work around." (Practitioner Participant 4)
Designer experience or efficacy	Remote engagements provide less personal satisfaction for the designer	1	"Nothing replaces the in-person joy of seeing somebody else get how something works – the sort of collective enjoyment over making something work is just not the same remotely." (Practitioner Participant 5)

5 reported two positive changes to remote prototyping and engagement processes because of the pandemic:

> [As a result of the pandemic, we] might end up including clients in more brainstorms, even if they're not located closely. I think there's a lot of value, in particular, in that. And even though they're a little bit painful in terms of the extra amount of work that goes into kind of coordinating all the results, there's so much value that they will bring to the table that you just 'don't get otherwise.'

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> In terms of mocking things up [the shift to remote design work] has been kind of just a reminder of just how fast you can do things with common objects around your house.

Student participants reported mixed perceptions of the impact of remote stakeholder engagements with prototypes on design process quality. Unlike practitioner participants, all 10 of whom reported that remote stakeholder engagement with prototypes need not ultimately affect the quality of design outcomes, six students reported that the overall impact of remote engagements was not detrimental to their design work, while four said that it was detrimental. In addition, several student participants described the remote nature of their stakeholder engagements as challenging in ways that practitioners did not. For example, Student Participant 9 said:

> But the in-person portion is really nice, because if you're running into an issue, sometimes over virtual it's really hard to communicate that [to instructors]. So, it can be really isolating. There's a lot of problem solving on your own.

5. Discussion

5.1. Usage of strategies for remote stakeholder engagement with prototypes

The use of 12 of the 17 strategies from prior research on general engagement with prototypes in front-end design (Rodriguez-Calero *et al.* 2020) by practitioner participants in remote contexts indicates some transferability to remote design. In addition, the limited number of strategies (two) from prior research that were clearly modified in remote contexts supports the transferability of strategies between in-person and remote design. The relatively small number of unique strategies (three) that emerged for remote engagements with prototypes in front-end design may provide additional evidence that most remote strategies overlap with previously described strategies, rather than being completely unique to remote contexts. Similarly, the fluid way in which practitioners discussed remote, in-person and hybrid stakeholder engagements strategies supports the transferability of strategies across remote and in-person contexts. This flexibility aligns with the findings of Coulentianos *et al.* (2020*a*) in a related study of prototyping strategies for stakeholder engagement in international design contexts, where designers were found to balance in-person and remote communication, among other factors, to collect stakeholder input effectively.

The absence of the remaining five strategies described in Rodriguez-Calero *et al.* (2020) as well as the low prevalence of several other strategies, has several potential explanations. Some strategies, such as "Task the stakeholder with creating or changing the prototype(s)" or "Introduce the prototype(s) to the stakeholder in the use environment" may be less feasible or effective in a remote engagement, as there is likely to be less opportunity to observe stakeholders in as much detail or maintain necessary guidance on the stakeholder's behavior. This explanation is in line with a report on the efficacy of remote work by type of task, which found that while most work in fields like engineering can be done remotely, "communicating with and guiding colleagues or clients" is among the most challenging tasks to carry out remotely (Lund *et al.* 2020). Other explanations for the absence of some

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strategies include the limited number of designers and design industries sampled in this study; different individuals, organizations and industries may have different approaches that were not captured in this research.

In addition, the 17 strategies described in prior work sometimes mapped to those reported by practitioners and students in overlapping or ambiguous ways. For example, the case described in Section 4.1.3 where Participant 3 reported showing a stakeholder only certain components of a product could reasonably be interpreted as presenting a deliberate subset of prototypes (strategy 10), prompting the stakeholder to select prototypes and prototype features (strategy 5), or both. This excerpt also includes strategy 3: showing the stakeholder multiple prototypes concurrently, which along with strategy 1: showing a single prototype, could apply to most engagement cases alongside other strategies. This ambiguity implies that (1) designers may often have multiple objectives and employ multiple strategies when using prototypes to engage with stakeholders, and (2) there are likely to be opportunities to further categorize and develop the 17 strategies in ways that improve their clarity and usefulness in structuring stakeholder engagements.

Regarding the three remote prototyping strategies for stakeholder engagement in front-end design that were not described explicitly by prior literature, the communication modes described – virtual communication platforms, physical prototypes sent to the stakeholder, and the use of an intermediary engagement facilitator as a stand-in for the designer – appear to broadly cover the types of remote engagement modes available to a designer. There is likely room for further expansion or subdivision of these strategies through future research, however. For example, there was evidence of the intentional use of either synchronous or asynchronous engagement strategies when digital or physical prototypes were sent to stakeholders, but it is not clear from our data whether and how these events might be described as independent prototyping strategies for stakeholder engagement.

Overall, student participants reported fewer strategies per participant than practitioners (roughly half as many when strategies that were used in limited ways to meet instructor and project sponsor expectations are excluded). These differences between practitioner and student participants may be because of the limitation of a course-based design environment, the change to a remote course format due to the pandemic and/or limited opportunities for in-person stakeholder engagement, or because student participants were not aware of the range of prototyping and stakeholder engagement strategies available to them due to limits of prior design experience and/or education. It is worth noting that student participants' strategies often appeared to be effective in the context of meeting the requirements of their course, but were not representative of the level of stakeholder feedback collected by practitioners with nominally similar prototyping and engagement strategies. This finding may highlight limitations of the project-based design course in replicating professional design practice. While it is not possible to fully determine the reasons for the difference in perceptions between practitioner and student participants in our data, nor the extent to which the pandemic may have influenced the lower number of strategies reported by student participants, this finding may still indicate a gap between engineering design education and professional practice worth considering for targeted educational interventions.

Despite student participants' comparatively limited usage and perceptions of stakeholder engagement strategies, students appeared to be effective in the use of

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digital prototyping and communication tools. Student participants demonstrated greater consideration and intentionality with digital prototypes and communication tools than with stakeholder engagement and prototyping strategies in general. This finding does not mean that student participants necessarily matched or exceeded the skills of practitioner participants in these areas, as these skills me be implicit and commonplace in professional work and therefore were not discussed by practitioners during interviews, but our data did not show a clear disparity between students and practitioners in digital communication and prototyping skills. Student participants have grown up using digital technologies, including those related to CAD software and video communication platforms, in ways that many practitioners may not have. As a result, students may be likely to apply these skills to problems in ways that may not be as intuitive to older engineers, as is supported by a study of problem-solving abilities of recent generations of students (Ting 2015). Student participants' digital literacy may also have been demonstrated by their awareness of the limitations of virtual communication formats and the related risk of miscommunication with nontechnical stakeholders, which was mitigated by the intentional use of higher-fidelity prototypes – a strategy which was shared by practitioners.

Additionally, while not the focus of this study, participants sometimes talked about prototyping strategies for remote stakeholder engagement in ways that overlapped with the back end of design. This overlap is in line with findings from Lauff *et al.* (2020), which described the use of prototypes in later design stages to persuade stakeholders to agree with a design direction or to collect stakeholder feedback to validate designs. Our results, as well as the cross-over in participants' discussion of front- and back-end strategies during this research, suggest that there is likely to be meaningful overlap across front-end and back-end design within the prototyping strategies for stakeholder engagement described in this work and others, which could be explored in future research.

5.2. Intentionality of strategy usage

Our findings demonstrate that engineering design practitioners' strategies for prototype usage during remote stakeholder engagements in front-end design were often intentionally tailored to suit specific design needs. This intentional use of strategies is consistent with other literature describing prototyping and stakeholder engagement strategies in general as applied intentionally for a given context during front-end design (Camburn *et al.* 2017), as well as literature specifically describing the use of prototyping strategies for stakeholder engagement during front-end design (e.g., Rodriguez-Calero *et al.* 2020; Coulentianos *et al.* 2020*a*,*b*, 2022). Significantly, practitioners discussed in-person, remote, and hybrid engagement practices as having unique advantages and limitations, which they leveraged strategically to meet specific design needs.

In the case of student participants, it seems likely that the presence and/or prevalence of some strategies reported were artifacts of the course requirements more than a representation of student participants' skills, indicating reduced intentionality in selecting strategies. In particular "Prompt the stakeholder to select prototypes and prototype features" appears to have been a likely derivative of a course requirement that student participants develop three independent design concepts before narrowing down to one, typically with input from other project

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stakeholders. Student participants appeared to ask stakeholders to make design decisions for them rather than approaching engagements with the strategic intent to elicit stakeholder perceptions in order to support their own decision-making. This finding indicates another possible limitation of the course-based design experience studied, as well as opportunities for changes to course structures to bring students' stakeholder engagement experiences closer to professional work and/or provide other forms of support for prototyping and stakeholder engagement skills, as has been called for in prior research (e.g., Viswanathan *et al.* 2014; Deininger *et al.* 2017, 2019).

5.3. Perceptions of remote stakeholder engagement with prototypes

While limitations to remote prototyping and communication strategies were reported, in some cases limitations were described as being overcome or converted to advantages, such as when increased and easier access to more stakeholders through digital communication offered new or more effective design opportunities, as has been described in previous research on remote design work (Li & Qiu 2006). In other cases, the limitations of remote engagements were described as a worthwhile trade for the higher financial cost of in-person engagements, which would have included higher travel or shipping costs, communication delays or staff time. Practitioners, who reported frequent combinations of in-person and remote stakeholder engagements with prototypes for projects, evaluated the costs and benefits of each modality of engagement when developing stakeholder engagement plans.

Compared to practitioner participants, student participants demonstrated fewer prototyping strategies for stakeholder engagement during front-end design, and perceived remote engagements as being more difficult and time-consuming than in-person engagements, as well as less effective. While student participants had limited in-person engagement experience as a point of reference, these results may still imply that students may benefit from additional scaffolding as they learn prototyping strategies for stakeholder engagement during front-end design when engaging remotely. With these gaps in students' understanding in mind, we propose recommendations for educators to support the development of relevant skills:

1. Reinforce the value of strategic intent in developing prototyping and stakeholder engagement plans.
2. Provide specific prototyping strategies for stakeholder engagement across in-person and remote formats.
3. Communicate the value and prevalence of remote and hybrid work in industry, along with general strategies to overcome challenges or leverage challenges into advantages.
4. Provide practical exposure to projects with opportunities for remote stakeholder engagement.

These recommendations overlap with calls for explicit, advance preparation of engineering students to perform often unfamiliar remote work effectively by Asadi *et al.* (2017), and calls to support students in overcoming low motivation due to the added challenges of remote design projects by Utriainen (2017). In addition, we propose that students' relative expertise with digital communication formats may

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be leveraged in remote design skills training. Connecting students' pre-existing knowledge of the advantages and limitations of digital communication tools to the intentional, strategic design of stakeholder engagement plans may help them overcome the challenges reported in this research and described by Utriainen (2017).

5.4. Limitations and recommendations for future research

This work is a starting point for the exploration of remote stakeholder engagement with prototypes in engineering design but, as discussed above, our sample size did not allow us to discern possible differences between industries or relationships between types of stakeholders, prototypes and engagement strategies. Larger sample sizes and the inclusion of participants from additional design industries would likely be needed to address these questions and to potentially identify additional engagement strategies. In addition, this study was not designed to assess the quality or effectiveness of strategies, which could be explored in future work. As our data collection was limited to a single mode due to the pandemic (interviews over a video call platform), observational or other research methods could also be used to expand this research, as well as to isolate front-end design activities by collecting data during the front-end of design projects rather than through reflective interviews that may take place after all design stages are complete. Controlled experiments could also be designed to study specific strategies and perceptions of students and/or practitioners in more detail. Additional study of remote engagement strategies in design cases not shaped by the transition to remote work and education during the COVID-19 pandemic may also illustrate alternate or complementary practices.

In addition, the division between front-end and back-end design was sometimes unclear in the data collected, potentially limiting the accuracy of counts of the number of participants who reported each strategy. Though we expect some level of transferability between the strategies and perceptions described for the design front-end in this research to later design stages, future research could explicitly explore remote prototyping and stakeholder engagement in back-end design or across design stages to further develop knowledge of prototyping and engagement strategies, as well as to clarify similarities and differences between design stages. Future work is also needed to differentiate between strategies focused on prototypes, communication formats, stakeholder interaction design, and so forth, within prototyping strategies for stakeholder engagement, which are not characterized individually in this study. More work is needed to develop and test pedagogical material and tools to teach engineering students how to conduct remote engagements effectively, as well. Finally, since this study was conducted as organizations and universities were adjusting to COVID-19 restrictions, additional work is needed to assess the strategies of practitioners and students during more typical design experiences and to compare our findings to pre- and post-pandemic practices.

6. Conclusion

The outcomes of this work support the field of engineering design in its response to the need for remote stakeholder engagements due to ongoing trends toward

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globalized, distributed design work, which have been accelerated by the COVID-19 pandemic. The usage of prototyping strategies for remote stakeholder engagements in front-end design was described. Most strategies were found to overlap with strategies described by prior literature that are not specific to remote engagement modes, though several of these strategies were adapted to serve different purposes in the remote context. In addition, three distinct strategies for prototyping in remote engagements were defined, which included the use of virtual communication formats, physical prototypes sent to remote stakeholders and third-party engagement facilitators standing in for a remotely located designer.

Designers' perceptions of the value and effectiveness of remote versus in-person prototyping strategies for stakeholder engagements were also summarized. The main findings from practitioner participants indicated that (1) while remote engagements may require more effort, advance preparation and strategic communication, the quality of engagement results and design outcomes can be comparable to in-person engagements, (2) remote engagement allows access to stakeholders who might not otherwise be available to the designer and (3) that even in primarily in-person work environments, prototyping strategies for remote engagement may add value and should be considered alongside in-person engagement when stakeholder engagement plans are developed.

Finally, practitioner participants' more nuanced understanding of remote engagements compared to student participants highlighted several recommendations for educators to better prepare engineering students for the hybrid and remote work they are likely to face as practitioners. These recommendations include (1) reinforcing the importance of strategic intent in developing prototyping and stakeholder engagement plans, (2) providing specific strategies for prototypes and stakeholder engagements across in-person and remote formats, (3) emphasizing the value and prevalence of remote and hybrid work in industry, along with general strategies to leverage opportunities and overcome challenges related to remote work and (4) providing practical exposure to projects with opportunities for remote stakeholder engagement.

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References

Asadi, N., **Guaragni, F.**, **Johannknecht, F.**, **Saidani, M.**, **Scholle, P.**, **Borg, J.** & **Panasiuk, D.** 2017 Success factors of an IPD based approach in a remote multidisciplinary team environment—reflections on a case study. In *21th International Conference on Engineering Design, ICED 17*. Design Society. https://hal.archives-ouvertes.fr/hal-01571582

Atman, C. J., **Adams, R. S.**, **Cardella, M. E.**, **Turns, J.**, **Mosborg, S.** & **Saleem, J.** 2007 Engineering design processes: a comparison of students and expert practitioners. *Journal of Engineering Education* **96** (4), 359–379; doi:10.1002/j.2168-9830.2007.tb00945.x

https://doi.org/10.1017/dsj.2023.23 Published online by Cambridge University Press

Baek, J. S., **Kim, S.** & **Harimoto, T.** 2019 The effect of cultural differences on a distant collaboration for social innovation: a case study of designing for precision farming in Myanmar and South Korea. *Design and Culture* **11** (1), 37–58; doi:10.1080/17547075.2019.1565400

Bogdan, C., **Ertl, D.**, **Falb, J.**, **Green, A.** & **Kaindl, H.** 2012 A case study of remote interdisciplinary designing through video prototypes. In *2012 45th Hawaii International Conference on System Sciences*, pp. 504–513. IEEE; doi:10.1109/HICSS.2012.46

Brill, O., **Schneider, K.** & **Knauss, E.** 2010 Videos vs. use cases: can videos capture more requirements under time pressure? In *Requirements Engineering: Foundation for Software Quality* (ed. R. Wieringa & A. Persson), pp. 30–44. Springer; doi:10.1007/978-3-642-14192-8_5

Camburn, B., **Viswanathan, V.**, **Linsey, J.**, **Anderson, D.**, **Jensen, D.**, **Crawford, R.**, **Otto, K.** & **Wood, K.** 2017 Design prototyping methods: state of the art in strategies, techniques, and guidelines. *Design Science* **3**, e13; doi:10.1017/dsj.2017.10

Cooper, R. G. 2019 The drivers of success in new-product development. *Industrial Marketing Management* **76**, 36–47; doi:10.1016/j.indmarman.2018.07.005

Coulentianos, M., **Rodriguez-Calero, I.**, **Daly, S.**, **Burridge, J.** & **Sienko, K.** 2022 Stakeholders, prototypes, and settings of front-end medical device design activities. *Journal of Medical Devices* **16**, 031010; doi:10.1115/1.4054207

Coulentianos, M. J., **Rodriguez-Calero, I.**, **Daly, S. R.** & **Sienko, K. H.** 2020a Global health front-end medical device design: the use of prototypes to engage stakeholders. *Development Engineering* **5**, 100055; doi:10.1016/j.deveng.2020.100055

Coulentianos, M. J., **Rodriguez-Calero, I.**, **Daly, S. R.** & **Sienko, K. H.** 2020b Stakeholder engagement with prototypes during front-end medical device design: who is engaged with what prototype? In *2020 Design of Medical Devices Conference*, p. V001T08A001. ASME; doi:10.1115/DMD2020-9020

Creswell, J. W. & **Poth, C. N.** 2016 *Qualitative Inquiry and Research Design: Choosing among Five Approaches*. Sage.

Deininger, M., **Daly, S. R.**, **Sienko, K. H.** & **Lee, J. C.** 2017 Novice designers' use of prototypes in engineering design. *Design Studies* **51**, 25–65.

Deininger, M., **Daly, S. R.**, **Sienko, K. H.**, **Lee, J. C.** & **Kaufmann, E. E.** 2019 Investigating prototyping approaches of Ghanaian novice designers. *Design Science* **5**, E6; doi:10.1017/dsj.2019.5

Dunlap, B. U., **Hamon, C. L.**, **Camburn, B. A.**, **Crawford, R. H.**, **Jensen, D. D.**, **Green, M. G.**, **Otto, K.** & **Wood, K. L.** 2014 Heuristics-based prototyping strategy formation: development and testing of a new prototyping planning tool. In *ASME International Mechanical Engineering Congress and Exposition (Vol. 46606)*, p. V011T14A019. American Society of Mechanical Engineers.

Hansen, C. A. & **Özkil, A. G.** 2020 From idea to production: a retrospective and longitudinal case study of prototypes and prototyping strategies. *Journal of Mechanical Design* **142** (3), 031115; doi:10.1115/1.4045385

Hennink, M. & **Kaiser, B. N.** 2022 Sample sizes for saturation in qualitative research: a systematic review of empirical tests. *Social Science & Medicine* **292**, 114523.

Jensen, M. B., **Elverum, C. W.** & **Steinert, M.** 2017 Eliciting unknown unknowns with prototypes: introducing prototrials and prototrial-driven cultures. *Design Studies* **49**, 1–31.

Jensen, L. S., **Özkil, A. G.** & **Mortensen, N. H.** 2016 Prototypes in engineering design: definitions and strategies. In *Ds 84: Proceedings of the Design 2016 14th International Design Conference*, pp. 821–830. Design Society.

https://doi.org/10.1017/dsj.2023.23 Published online by Cambridge University Press

Lande, M. & **Leifer, L.** 2009 Prototyping to learn: characterizing engineering students' prototyping activities and prototypes. In *DS 58-1: Proceedings of ICED 09, the 17th International Conference on Engineering Design (Vol.* **1**). Design Processes.

Larsson, A. 2007 Banking on social capital: Towards social connectedness in distributed engineering design teams. *Design Studies* **28** (6), 605–622; doi:10.1016/j.destud.2007.06.001

Lauff, C. A., **Knight, D.**, **Kotys-Schwartz, D.** & **Rentschler, M. E.** 2020 The role of prototypes in communication between stakeholders. *Design Studies* **66**, 1–34.

Lauff, C., **Menold, J.** & **Wood, K. L.** 2019 Prototyping canvas: Design tool for planning purposeful prototypes. *Proceedings of the Design Society: International Conference on Engineering Design* **1** (1), 1563–1572; doi:10.1017/dsi.2019.162

Li, W. D. & **Qiu, Z. M.** 2006 State-of-the-art technologies and methodologies for collaborative product development systems. *International Journal of Production Research* **44** (13), 2525–2559; doi:10.1080/00207540500422080

Lund, S., **Madgavkar, A.**, **Manyika, J.** & **Smit, S.** 2020 *What's Next for Remote Work: An Analysis of 2,000 Tasks, 800 Jobs, and Nine Countries*, pp. 1–13. McKinsey Global Institute.

Mathias, D., **Hicks, B.**, **Snider, C.** & **Ranscombe, C.** 2018 *Characterising the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development*, pp. 1257–1268. Design Society; doi:10.21278/idc.2018.0445

Menold, J., **Jablokow, K.** & **Simpson, T.** 2017 Prototype for X (PFX): a holistic framework for structuring prototyping methods to support engineering design. *Design Studies* **50**, 70–112.

Mohedas, I., **Daly, S. R.** & **Sienko, K. H.** 2014 Student Use of Design Ethnography Techniques during Front-end Phases of Design, pp. 24.1126.1–24.1126.9. https://peer.asee.org/student-use-of-design-ethnography-techniques-during-front-end-phases-of-design

Mohedas, I., **Sienko, K. H.**, **Daly, S. R.** & **Cravens, G. L.** 2020 Students' perceptions of the value of stakeholder engagement during engineering design. *Journal of Engineering Education* **109** (4), 760–779; doi:10.1002/jee.20356

Nelson, J. & **Menold, J.** 2020 The value of prototyping: an investigation of the relationship between the costs of prototyping, perceived value, and design outcome. In *32nd International Conference on Design Theory and Methodology (DTM) (Vol.* **8**), p. V008T08A041; doi:10.1115/DETC2020-22104

Patton, M. Q. 2015 *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*. Sage.

Reimlinger, B., **Lohmeyer, Q.**, **Moryson, R.** & **Meboldt, M.** 2020 Exploring how design guidelines benefit design engineers: an international and global perspective. *Design Science* **6**, e9; doi:10.1017/dsj.2020.3

Rodriguez-Calero, I. B., **Coulentianos, M. J.**, **Daly, S. R.**, **Burridge, J.** & **Sienko, K. H.** 2020 Prototyping strategies for stakeholder engagement during front-end design: design practitioners' approaches in the medical device industry. *Design Studies* **71**, 100977; doi:10.1016/j.destud.2020.100977

Rodríguez-Calero, I., **Daly, S. R.**, **Burleson, G.** & **Sienko, K. H.** 2023 Prototyping strategies to engage stakeholders during early stages of design: a study across three design domains. *Journal of Mechanical Design* **145** (4), 041413.

Sanders, E. B.-N. & **Stappers, P. J.** 2008 Co-creation and the new landscapes of design. *CoDesign* **4** (1), 5–18; doi:10.1080/15710880701875068

Ting, Y. L. 2015 Tapping into students' digital literacy and designing negotiated learning to promote learner autonomy. *The Internet and Higher Education* **26**, 25–32.

https://doi.org/10.1017/dsj.2023.23 Published online by Cambridge University Press

Utriainen, T. 2017 Perceived difficulty of design thinking activities in co-located and remote environments. *CERN IdeaSquare Journal of Experimental Innovation* **1**, 21; doi: 10.23726/CIJ.2017.460

Viswanathan, V., **Atilola, O.**, **Goodman, J.** & **Linsey, J.** 2014 Prototyping: a key skill for innovation and life-long learning. In *2014 IEEE Frontiers in Education Conference (FIE) Proceedings*, pp. 1–8. IEEE; doi:10.1109/FIE.2014.7044423

https://doi.org/10.1017/dsj.2023.23 Published online by Cambridge University Press