Practicing Engineers' Use of Prototyping Strategies to Engage Stakeholders During Front-End Design

by

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Abstract

The use of prototypes in engineering design has historically consisted of building, testing, and refining the form and function of concept solutions. However, diverse stakeholders, who impact or are impacted by concept solutions, directly affect design success, including a solution's form and function. Because prototypes enable communication and collaboration, they can be powerful tools to support stakeholder engagement at the earliest stages of design to inform problem definition and concept exploration. However, studies suggest prototypes have traditionally been prioritized during the mid to late stages of a design process and have not been used to their full potential during the design front end, including to engage stakeholders. Further, specific prototyping strategies that can be leveraged to engage stakeholders during front-end design have not been deeply explored in the literature.

Thus, my work used qualitative research methods to identify prototyping strategies design practitioners used when engaging stakeholders during the early phases of design. I performed semi-structured interviews with 22 design practitioners working in multinational and global health companies and used an inductive analysis technique. The 17 prototyping strategies identified elucidated distinct aspects of stakeholder engagement with prototypes during early design, including prototype quantities, resolution, and interactions. The study additionally demonstrated practitioners' intentionality for prototype use. Practitioners used prototypes as tools to promote meaningful dialogue to gather information for requirements and specifications development, and to aid in early concept exploration.

To investigate the transferability of the prototyping strategies from the medical device domain to other design contexts, I compared strategy use in 12 medical device design practitioners in the first study to findings from interviews with seven automotive and seven consumer products design practitioners. The findings from this study showed that all 17 previously identified strategies were used to some extent across the two additional design domains, and at least 12 were used in all three design domains. Further, I described common ways the prototyping strategies were leveraged across design domains as well as how some strategies were adapted based on the project context.

Finally, I constructed three in-depth case narratives from the design practitioner interview data to richly describe how the prototyping strategies were used in the practitioners' specific project contexts. These narratives highlighted how practitioners intentionally used prototypes in practice to answer specific design questions and illustrated how their strategies worked in service of their goals. Then, based on the data, I created a prototyping tool to support training and education on how to use prototypes to engage stakeholders in the early stages of design. The tool has potential to expand engineering designers' repertoire of strategies for engaging stakeholders through prototyping early in design processes.

This collection of studies provides guidance on concrete ways for engineering design practitioners to leverage prototypes earlier within a design process, and to do so with intentionality to better understand design problems grounded in stakeholder needs and priorities. The findings on prototyping strategies across design domains contribute to the growing body of design methodology literature, providing a collection of methods broadly applicable in design practice and education. The narratives place these strategies within the context of actual engineering design projects, providing examples of contextualized design processes critical for

design education. By studying practitioners to delineate effective practices and guide interventions in engineering education, this scholarly contribution narrows the gap between research, practice, and education.

Chapter 1 Overview, Motivation, and Background

1.1 Introduction

Designing successful products requires incorporating aspects of the design context, including stakeholders—people who impact or are impacted by design outcomes [1–3]. Interpreting and synthesizing information from stakeholders can be challenging for design practitioners because stakeholders may not give feedback in terms of product requirements and engineering specifications [4,5]. Accordingly, designers need to employ different tools and techniques, including prototyping early in design processes, to scope design problems, define product requirements and develop engineering specifications grounded in stakeholder information [6–8]. Prototypes are design tools traditionally used across disciplines for verifying and validating developed designs against established criteria. However, existing reports of prototype use suggest that they are not leveraged to their full potential during the early, "front end" of design activities including problem definition, requirements elicitation and specifications development, through early concept generation [7,9–12].

Prototypes are valuable design tools for communication and collaboration [13–15]. However, the literature lacks a systematic exploration into how prototypes are used for stakeholder engagement when defining design problems, developing design requirements, and translating requirements into engineering specifications. Furthermore, many known strategies are described broadly as general principles, lacking the details required for their successful implementation by novice design practitioners [16–18]. Lastly, various published studies focus on novice designers' prototyping behaviors (e.g., [19–23]), potentially overlooking the strategies

of practitioners who have developed expertise outside of educational settings. Thus, this dissertation investigates design practitioners' intentional use of prototypes to engage with stakeholders during the earliest phases of design.

1.2 Background

1.2.1 Prototypes in engineering design processes

Traditionally, prototypes have been conceptualized as physical or analytical "approximations" to an intended design outcome used to test and evaluate concepts [24], or validate design decisions [25]. However, broader prototyping roles exist in design practice such as communication, collaboration, and learning [13,14,26,27]. Houde and Hill [28] provide a broad definition of prototypes as any representation of a design idea, regardless of its medium, which is adopted throughout this dissertation.

Prototyping is reported as an ongoing design process activity [14,29], although engineering design prototyping research tends to be a solution-focused stage with emphasis placed in time, cost, and performance tradeoffs. A state-of-the-art review highlighted different prototyping techniques from the literature with their respective design purpose, and described their planned combination as an overarching prototyping strategy [30]. For instance, prototyping techniques such as "iterative prototyping" and "parallel prototyping" correspond to purposes such as refinement of the design concept, and exploration of design solutions, respectively. Some scholars refer to prototyping strategies as the goal-oriented decisions that guide actions in a broad prototyping effort within a product development timeline [31,32]. Prototyping strategies have also been described as the actions taken within a prototyping development process [33], or best practices, and guidelines [34–36]. Moreover, research on strategies has emphasized the impact of prototype form, mode of presentation, function, fidelity, fabrication, resource

expenditure (i.e., time and cost), on the design outcomes associated with the management of these factors [30,33,37–39]. A summary of this research is provided in Table 1.

Table 1 Definitions for key terms associated with prototyping.

Term	Definition	Source
Strategy	Practitioners' employed methods; e.g., designers begin each iteration at a component level; designers revert back to previous versions if they reach a local maximum; designers continually build upon the list of evaluations performed on each prototype.	[33]
	"The set of choices that dictate actions that will be taken to accomplish the development of prototypes."	[31,32]
	How prototypes are planned for in a product development project.	[40]
	A planned combination of techniques to a achieve a set of objectives.	[30]
	Decisions made for media, manufacturing technique, prototype test, parallel concepts, iterations, and system-level integrations.	[29]
Techniques	"Guides the embodiment of a prototype" addressing "how to prototype," e.g., iteration.	[30]
Purpose	Responds to the question, "why should we build a prototype;" e.g., answer questions regarding functionality, use the prototype as a means of visual aid for initiation of discussions.	[41]
Objectives	Prototyping affordances; e.g., building to think, learning faster by failing early, giving permission to explore new behaviors.	[42]
	Goals; e.g., active learning, exploration, communication, refinement.	[30]
	Goals that are influenced by new knowledge acquired through prototyping (derived from examples), e.g., optimize for transportation and installation.	[43]
	Design targets or thresholds defined by an equation or inequality (derived from examples); e.g., "maximize distance traveled."	[22,31, 38,44]
Heuristics	Action taken upon the strategic decision (derived from example); e.g., build a scaled prototype, support building with analytical calculations.	[32,45]
Process	Cycle of planning, execution, and evaluation of prototype against project objectives.	[38]

Definitions of key terms from the prototyping literature have a strong orientation towards optimization of design solutons. More recent work has explored how prototypes play a role in communication in an industry design process [15] and the impact of different prototype formats in the information elicited [34,40,46,47]. While this work is foundational to better understand prototyping processes, it provides limited understanding of methods applicable to engagement of stakeholders with prototypes during the front end of design when designers work to define, specify, and verify needs, priorities, requirements, and objectives.

1.2.2 Stakeholder engagement during the front end of design

The front end of design is characterized by its ambiguity and uncertainty [48,49]. During the early stages of design, engineering design practitioners gather information to better understand design problems and opportunities and generate initial design solutions [3,9], as well as identify key points of leverage and information sources [17]. Learning about stakeholders' successes, challenges, values, behaviors, and motivations in their current environments is a crucial and challenging undertaking of front-end design work [1,2,48,50,51] that can lead to product and requirements definitions that correspond to the needs of end-users and stakeholders, guiding solutions what work within the context in which they are situated [8,52]. At the outcome of engaging stakeholders during the front-end are product definitions and specifications that shape how product development processes are approached [7,49]. Over time, decision errors and changes in project scopes become harder to rectify due to sunk costs [10,53], making proficient front-end design work a key factor for design success.

Synthesizing stakeholder input into design requirements, engineering specifications, and revised problem statements that correspond to real user needs is a substantial undertaking. Designers often need to reconcile competing goals and expectations from various stakeholder groups [50,54,55], and manage miscommunication with stakeholders when interacting across different backgrounds and areas of expertise [5,56–58]. Therefore, it is essential that designers develop the skillset to navigate the front-end developing a deep understanding about the stakeholder's lives and contexts to base their design solutions.

Multiple methods support stakeholder engagement such as observations, interviews, focus groups, surveys, group brainstorming, co-creative workshops, contextual inquiry, design ethnography, and the use of early prototypes [51,59–63]. More specifically, designers need to prepare effective interview protocols [64], perform data analysis and synthesis [65], and use

insights to make design decisions. During interactions with stakeholders, designers must develop rapport with stakeholders [25,66,67], encourage stakeholders to analyze and integrate ideas and concepts [68,69], and verify stakeholder conclusions and interpretations [4,5,70]. Notably, evidence that suggests there are gaps in stakeholder engagement and information gathering behaviors between novices and practitioners—practitioners are known to have expansive representations of problems, leveraging key sources of information, and they demonstrate following more rich and complex design processes [9,17,18,71,72].

Front-end prototyping spans various exploratory and generative tools that have emerged from practice in Human-Computer Interaction (HCI), Co-design and adjacent design disciplines. They have been conceptualized as prototype types based on what they are used for by the designer. Probes, toolkits, and prototypes may include 2D and 3D representations, diaries, cards, games, props, and enactments for priming and probing participants on a specific topic, understanding their experiences, and generating new ideas [73]. Pretotypes on the other hand are more experiential in nature, getting to the core value proposition before committing development resources [74]. Experience prototypes refer to "any kind of representation in any medium that is designed to understand, explore, or communicate what it might be like to engage with the product, space, or system" being designed through actively participating in the experience [75]. Provotypes embody tensions and extremes to be resolved collaboratively among stakeholders [76] and live prototypes refer to prototypes that are iterated on actively in real time while engaging a stakeholder [77]. However, limited research exists to describe detailed and explicit strategies for how to use these and other prototype types within various forms of stakeholder engagement, particularly in engineering design practice.

1.3 Dissertation Overview

The contents of this dissertation are summarized hereafter by chapters.

Chapter Two consists of a study investigating the prototyping strategies for stakeholder engagement through data collected from 22 medical device design practitioners. Following a qualitative research approach, semi-structured interviews were analyzed inductively following a constant comparative method among coders. The finalized codebook from that process serves as the main findings, with code definitions and exemplary quotes. The most and least salient codes were individually described, and individual strategies were discussed with respect to the broader literature.

Chapter Three describes a study exploring the transferability of the 17 prototyping strategies for stakeholder engagement from the initial domain of medical devices. The data sources in this study consisted of 26 semi-structured interviews with design practitioners in the initial domain and two other design domains (consumer products and automotive) which were deductively analyzed using the codebook developed in Chapter Two. Further, use scenarios for the strategies were compared across participants' projects. The findings in Chapter Three suggest the strategies are transferable because they occur in other design domains.

Chapter Four describes a study of prototyping strategies using a different analytic technique. The aim of the study was to translate how prototyping strategies are used by design practitioners to engage stakeholders in the context of a specific engineering design project. The method employed techniques from case study research applied to the interview transcripts to construct case narratives. The results consist of three main practitioner narratives with in-depth descriptions of how particular strategies were used within a specific project context. These narratives provide pedagogical materials to illustrate how practitioners make use of prototypes to

elicit input from stakeholders. Further, these narratives were synthesized to create a tool to support students and to inform recommendations for engineering education.

Finally, Chapter Five summarizes the studies from Chapter Two through Chapter Four. Then, a discussion of themes across the three studies highlight the use of prototypes for co-exploration, managing stakeholders' expectations, and engaging end-users in early design process activities. The chapter ends with implications for design practice and education in engineering, and a description of potential research directions for future work.

1.4 Dissertation Aims and Methods Overview

1.4.1 Aims and Research Questions

This dissertation investigated design practitioners' prototyping strategies to engage stakeholders during front-end design activities, including problem definition, requirements and specifications development, early concept generation, selection, and development. The following objectives guided this work:

1. Develop design practitioners' prototyping strategies for stakeholder engagement during the front end of design (Chapter Two).
2. Examine the use of prototyping strategies for stakeholder engagement during front-end design across multiple domains (Chapter Three).
3. Develop pedagogical materials and guidelines for practice-based prototyping strategies for stakeholder engagement (Chapter Four).

Corresponding to the dissertation aims, the overarching research questions for the studies were: 1) *What prototyping strategies do design practitioners use to engage stakeholders in the front end of design?* and 2) *How do design practitioners employ strategies to engage stakeholders during the front end of design?*

To address these research questions, I used qualitative methodologies because its strengths lie in finding explanations through rich descriptions of processes connecting people, situations, and events [78,79]. Qualitative research methods bring focus to *how* things happen from the participants' perspective, (i.e., exploratory work) as opposed to measuring quantities [78]. Further, qualitative methods are well-suited to describe broad concepts in design studies [80], and have been previously used to investigate design phenomena (e.g., [16,81–84]).

1.4.2 Data collection and analysis

The data sources for the studies described in this dissertation consisted of semi-structured interviews lasting between 1-1.5 hours per participant. Interview studies are well-positioned to report on detailed descriptions through the integration of multiple perspectives from members of a group [85], i.e., design practitioners.

The semi-structured interview protocol was collaboratively and iteratively developed following best practices [86], and written to elicit concrete stories of specific experiences where practitioners used prototypes rather than reporting general methods and principles.

Across the studies, participants were selected using a purposeful sampling technique [79] with the criteria that they were design practitioners with prototyping and stakeholder engagement experiences in front-end design activities and had work experience in the design domains studied. Selecting participants through a purposeful sampling technique such as the one employed in this work, more importantly, can help establish comparisons on the emergence of patterns between individuals, or settings during data analysis [78].

Multiple analytic techniques guided the work presented in Chapter Two through Chapter Four. Beginning with Chapter Two, the process was inductive consisting of initial coding of the interview data to begin characterizing what would constitute a prototyping strategy for engaging

stakeholders. Themes were developed into codes following the constant comparison method [87,88], and then included in a codebook which gave each code a name, definition, and exemplary participant quotes. The process of refining the codebook was collaborative involving various members of the research team. Chapter Two established the basis to approach the analysis deductively in the study described in Chapter Three. Using a deductive analytic approach was suitable for its usefulness in exploring the applicability of prior findings to other contexts [89,90]. Lastly, Chapter Four examined the inductive and deductive analyses of the prior studies and looked across participants' interviews for evidence of broad use of strategies and rich project details. With that knowledge and informed by case study research guidelines [79], I constructed three case narratives based in the coded interview transcripts of three design practitioners from different domains, which placed the strategies in the specific context of front-end design projects. Methods for each study are included in the study's respective chapter as follows.

Chapter 2 Prototyping Strategies for Stakeholder Engagement During Front-End Design: Design Practitioners' Approaches in the Medical Device Industry[1]

Abstract

Prototypes are fundamental tools used throughout design processes. During early design stages, including problem definition and concept development, prototypes can support stakeholder engagement, which is considered critical for success. However, the ways in which engineering designers leverage prototypes within front-end stakeholder engagements are not well described in the literature. This research explored front-end prototyping strategies for stakeholder engagement through semi-structured interviews with medical device design practitioners. Our research findings describe seventeen strategies design practitioners used to engage stakeholders during front-end design activities. The findings add rich detail to the existing strategies broadly described in the literature, and have implications for designers across expertise levels, as they can be used to develop intentional approaches to engage stakeholders during front-end design.

2.1 Introduction

Design is sometimes described as domain-specific; design methods, tools, stakeholders, and artifacts vary across disciplines [91]. Design is also described as domain-general because there are broadly applicable practices that span multiple design disciplines [82,91–93]. Examples of domain-general practices include the gathering of information prior to the development of a

[1] This chapter was published in 2020 in Design Studies [146] with co-authors Marianna Coulentianos, Shanna Daly, Jocelyn Burridge, and Kathleen Sienko.

solution and the use of intermediate representations of problems and solutions [92], including prototypes. The ways in which prototypes are used can be domain-specific or domain-general as well.

Within engineering design, prototypes are often recommended for use in understanding and evaluating promising design concepts in mid to late design process phases, evidenced by design practice textbooks (e.g., [24,25,94]). Engineering design "back-end" prototyping strategies have focused on the number and order (e.g., in parallel, in series) of prototypes to use, and how to embody intermediate representations (e.g., physical, virtual) [31,44], including strategies for selecting prototype manufacturing and testing techniques [29].

Prototypes can also contribute to design success if used in the "front end" of design. The front end can broadly be defined as including background research, needs finding, problem scoping and definition, requirements or attribute elicitation, specifications development, concept generation, and concept development [9,10,24]. The front end presents unique challenges; for example, designers' understanding of problems and solutions co-evolve [95] in a process that lacks the structure of later design execution stages [11]. A key factor in design success is proficient front-end work. Gupta and Wilemon [48] noted that product development delays were attributed to inadequately executed front-end design activities, specifically, poorly defined requirements. Thomke and Fujimoto [96] described the association between product failure and the failure to "front-load," emphasizing the importance of "shifting problem solving trajectories upstream" to accelerate product development through the identification of problems and solutions earlier in a design process. A properly executed front end entails conducting fast, iterative cycles of representing early ideas in tangible forms; testing early ideas with customers or users; collecting customers' and users' feedback; and revising design requirements [7].

Some prototyping research in the engineering design literature encourages the use of prototypes to engage stakeholders during front-end work, with stakeholders defined as anyone who impacts or is impacted by the design [97]. For instance, studies have focused on engaging stakeholders with prototypes to uncover design requirements [46], seek stakeholder feedback on proposed solution concepts [47,98,99], and consider stakeholders' wants, needs, and priorities [100,101]. Although the field of human-computer interaction and co-design processes have described prototyping uses broadly, including throughout front-end design phases [28,102], traditional engineering design literature has described prototyping uses more narrowly, typically focusing on usage during the later phases of design. Further, while design practitioners may leverage front-end prototyping strategies with stakeholders, these uses have not been documented extensively in the literature, as the existing front-end prototyping literature has primarily focused on novice designers' approaches (e.g., [103,104]). Additionally, known strategies would benefit from nuanced details necessary for successful implementation by others. For example, human-centered design methods call for designers to perform rapid prototyping and obtain feedback [105], but the provided methods embed additional choices within their stepwise processes without necessarily providing the specific actions that may lead to successful execution.

Thus, our study sought to identify specific strategies used by design practitioners during front-end design engagements with stakeholders. We chose to focus this initial investigation on design practitioners from a specific design domain—medical devices. Similar to other industries, medical device design practitioners typically engage with stakeholders throughout multiple phases of design processes. However, medical device design practitioners also engage with stakeholders, particularly users, when performing user need analyses, human factors engineering,

and field trials to comply with regulatory requirements and standards [106]. Further, medical device design processes generally explore specific clinical needs [107] through the use of methods including contextual inquiry and direct observations [57,108], which necessarily engage stakeholders in some capacity. The findings from our study can inform novice and practitioner design methodologies within medical device design contexts as well as support engineering education and training.

2.2 Background

2.2.1 Prototyping in engineering design

Prototypes can be conceptualized as "approximations" of a product [24]. They have historically been defined within engineering design as "physical models of the product that are tested in some way to validate the design decisions that have been made up to that point in the design process" ([25], p. 370). However, prototypes can be created in various forms and formats, including physical models and virtual simulations, and represent whole ideas or components of an idea [24]. Recent engineering design research suggests that prototypes are being used throughout a design process [14]. A broad definition of prototyping, which is adopted in this paper, encompasses creating "any representation of a design idea regardless of medium" [28] through which concepts can be discussed, changed, and negotiated [109].

Since prototyping has long been recognized by professionals as an effective and necessary design activity [6,13], numerous strategies exist to guide engineering designers in using prototypes for product testing, evaluation, and refinement [33] once design objectives have been defined. Camburn et al. [30] described a prototyping strategy as the "planned combination of techniques to achieve an objective." Examples of more specific prototyping strategies include "begin each iteration of a design at a component level" [33]; "support building with analytical

calculations" [32,36]; and develop prototypes that adhere to a "reduced" version of design targets when appropriate [30,110]. Engineering design processes typically position prototyping-related content after concept selection [25,110,111]; as such, many prototyping strategies emphasize later design phase idea testing and refinement. However, prototypes serve as essential tools that can be used throughout a design process, including in early stages [27].

Prototypes support communication between designers and stakeholders and encourage stakeholders to provide feedback that can inform design decision making during early design phases [52,112,113]. Lauff et al. [14] further described the value of using prototypes for conveying concepts, assisting designers with gathering stakeholder feedback, facilitating negotiations, and persuading others. Prototypes have also been shown to be used during engagements with external stakeholders during downstream phases of a design process when it is too late to include the stakeholders' feedback [15]. In addition, Jensen et al. [46] discussed the relationship between prototype functionality and stakeholder involvement with respect to a company's ability to discover design requirements at different design stages. They argued that both functional and non-functional prototypes produced during the early stages of design helped designers elicit a wide variety of requirements in an industry product development context. Broader literature, including outside the scope of engineering design, is described in more detail in section 2.2.3 Prototyping for stakeholder engagement.

2.2.2 Stakeholder engagement during front-end design

Engaging diverse stakeholders is a crucial activity of front-end work that affects early evaluations and iterations of ideas [11]. Designers leverage a variety of methods to gather information from stakeholders, including interviews, questionnaires, focus groups, group brainstorming [5], and observations [2]. In other words, stakeholder engagement encompasses

information gathering, communication, collaboration, and other activities that involve stakeholders in a design process. Studies have stressed that engagement with stakeholders during the earliest phases of design leads to the definition of product requirements that better fit the needs of end users and stakeholders [7], as well as better fitting the context in which products will be deployed [8].

Engaging stakeholders during the front end of design can be a challenging task. In a study documenting medical device design professionals' challenges in complying with regulatory requirements pertaining to stakeholder engagement, Privitera et al. [107] identified multiple barriers, including several that are relevant to designers' interactions with stakeholders. For instance, making sense of unarticulated user requirements, managing users' expectations of what kinds of products can be feasibly designed, reconciling conflicting stakeholders' opinions, obtaining permission and balancing the associated increased development times to conduct formal engagements such as contextual inquiry and formal usability testing, and encouraging users to envision alternative uses or clinical approaches from their training. Martin and Barnett [114] argued the lack of formal streams to gather and integrate stakeholder information in design decisions may result in delivering a product that while technically sound, may poorly fit the stakeholders' needs, workflow, and context.

In addition to design practitioners, novice designers have been reported to face diverse obstacles when engaging stakeholders. Some examples include covering relevant topics to inform subsequent design decisions during stakeholder interviews [115], navigating the subjectivity characterizing stakeholder input, discerning between relevant and irrelevant information for design [116], and learning about the appropriate contextual factors that may impact the design [117].

Despite the challenges designers might face, an intentional approach for incorporating multiple stakeholders' voices in design decisions can have positive impacts on stakeholders, the designed product, the team, and the organization involved in the design, as was shown in a multiple stakeholder, medical device design context [118]. As such, designers must prepare effective protocols for eliciting relevant information [64], and bridge communication and disciplinary boundaries [57]. Designers must also develop rapport with stakeholders [66], encourage stakeholders to analyze and integrate ideas and concepts [68,69], verify stakeholder conclusions and interpretations [5,70], and use the gathered information to make design decisions. Prototypes may be especially useful for overcoming some of the presented challenges designers face when engaging stakeholders. However, specific strategies to support stakeholder engagement, especially during the front end, have been a limited focus of engineering design research.

2.2.3 Prototyping for stakeholder engagement

Prototypes act as shared representations between designers and stakeholders that can be perceived, experienced, and analyzed [119,120]. Prototypes can support stakeholders and designers in discussing abstract ideas (e.g., design requirements in terms of what a design should "do"), as they provide a real, tangible representation of a design concept [121]. Prototypes can be created to reveal both technical and contextual design considerations, which ultimately determine whether a developed product will be relevant to the stakeholders' needs and expectations [7,122]. For instance, prototypes can demonstrate technical shortcomings [123], prompt new behaviors [42], and make unanticipated requirements explicit [46].

Several scholars have examined the effects of prototype characteristics, like fidelity and format, with respect to the outcomes of stakeholder engagements. Rudd, Stern, and Isensee [124]

summarized the pros and cons of using low- and high-fidelity prototypes with stakeholders. Low-fidelity prototypes were deemed useful as early communication tools to establish common ground between the users and the designer and to gather requirements, but low-fidelity prototypes lacked the refinement needed for accurate testing and the uncovering of design shortcomings. In addition to fidelity, prototype aesthetics have been shown to affect users' appraisals and task performance [125]. Tiong et al. [34] showed that low fidelity prototypes were best used to evaluate core concepts and basic assumptions with users, but that prototypes of increased dimensionality (i.e., functionality, interaction, and resolution) were most useful for more refined and targeted design questions. Another factor identified as an important consideration when prototyping was the format, referring to how a prototype takes shape (e.g., sketch or 3D physical format). Tangible prototypes, which have a physical format, have resulted in stakeholders regarding concepts more positively [126], and elaborating more on their answers to the designer's questions [47]. Deininger et al. [47] emphasized that in their study, there was not a single prototype format that consistently elicited more thorough responses across stakeholder types, and importantly, that the questions being asked mattered.

A variety of prototype types used for stakeholder engagement have been described in the human-computer interaction and human-centered design literature. For example, "experience prototypes" represent a sensory experience, which can be passive (i.e., like looking at a storyboard of an experience), or active (i.e., like living through an experience which mimics the product, space, or system being designed) [75]. Additionally, "provotypes," which are designed objects meant to provoke a reaction in stakeholders and subsequently enable them to express their feelings and reflect on the experiences of interacting with the object, have been used to explore abstract concepts with users and experts [76]. Horst and Matthews [77] used "live

prototypes" to describe prototypes that can be modified during stakeholder engagements and can serve as a vehicle to collaborative problem formulation and solving, rapid iteration, and consensus building among stakeholders. Live prototypes uncovered misalignments between stakeholders so that they could be resolved in situ [77].

In co-design, probes including diaries and cameras, toolkits including 2D and 3D parts, pictures, and buttons, and prototypes have been discussed as having roles in problem exploration and inviting stakeholder participation [73]. These objects have facilitated different levels of interest and creativity among stakeholders [127], thus enabling different forms of stakeholder engagement, that include providing feedback about design concepts, and co-creating design solutions.

The aforementioned studies indicate that certain prototype types may be better suited to fulfill specific goals, but how these prototypes are leveraged during stakeholder engagements can also impact the type and quality of the interaction and information elicited. Further, much of the work highlighted in this section stems from areas of human-computer interaction, human-centered design, and co-design. Participatory approaches to design and prototyping remain largely within disciplinary boundaries and their integration into engineering design practitioners' design processes is not well understood. More work is needed to understand the intersections of prototyping strategies and stakeholder engagement in engineering front-end design processes.

2.3 Research methods

This study was guided by the following research question: What prototyping strategies do design practitioners use to engage stakeholders in the front end of design?

We leveraged qualitative research methods to answer this research question. A qualitative research approach enabled us to collect in-depth descriptions, a foundation of qualitative analysis

[79], of participants' experiences leveraging prototypes with stakeholders during front-end design activities. Further, a qualitative research approach enabled us to gather concrete experiences and perspectives that were detail-rich, as opposed to generalizations [85] or self-identified general strategies. We used an emergent approach, a method in which themes were derived inductively from the data [79,88]. This methodological decision was informed by our goal to identify strategies used across participants based on the experiences they described.

Qualitative research studies aim for transferability of findings, which involves articulating rich descriptions that support the translation to other contexts [79]. Aligned with this goal of transferability, our approach aimed to describe specific ways practitioners used prototypes to engage stakeholders during front-end design and explain patterns and variations among practitioners' approaches, including details about their design contexts that drove their decisions.

2.3.1 Participants

Practitioners from the medical device design industry were recruited as a preliminary design domain of focus, to provide some consistency among the types of design artifacts discussed. We initially contacted potential participants through personal networks and connections established at a medical device design conference. Prior to enrollment in the study, prospective participants completed an online survey consisting of demographic and prior experience questions. Using a purposeful sampling technique [79,128], participants who reported using prototypes to engage stakeholders were invited to participate in the study. Two participants recruited did not complete the online survey, because they were referred to us by colleagues based on their previous experiences using prototypes in past design projects.

Participants included 22 design practitioners from 16 medical device companies who had used prototypes for stakeholder engagement during the design front end of a mechanical or electro-mechanical product. Nine participants worked in companies with 10 000 employees (large), one in a firm with 50-200 employees (medium), and 12 in firms with 1-49 employees (small), addressing clinical needs in the United States, European Union, and in global health markets. Most participants had job titles aligning with engineering design (n=14) although some had training in other disciplines, including product design and design research. Their job roles varied; many had senior, lead, or principal design engineering, product design, design research, or technology management roles. As such, the term design practitioner is used broadly to represent variation among backgrounds, job roles, and years of design experience (mean=11.9 ± 9.3 years).

The University of Michigan Institutional Review Board reviewed and granted the study an exemption and consent was obtained from each participant prior to the interviews. Participant information is presented in Table 2.

Table 2 Participants.

Participant ID	**Gender**	**Age**	**Highest degree**	**Design experience (years)**	**Job tenure (years)**	**Company size**
Participant A	Male	34	Master's	6	4	Small
Participant B	Female	24	Bachelor's	1	1.75	Small
Participant C	Female	35	Master's	9	3	Small
Participant D	Female	38	Bachelor's	17	2	Small
Participant E	Male	31	Master's	6	0.67	Small
Participant F	Female	29	Bachelor's	6	6	Small
Participant G	Male	56	Bachelor's	30	24	Large
Participant H	Female	28	Master's	8	8	Small
Participant I	Male	42	Master's	17	10	Small

Participant ID	Gender	Age	Highest degree	Design experience (years)	Job tenure (years)	Company size
Participant K	Female	27	Master's	5	3.5	Small
Participant N	Female	37	Doctorate	6	6	Small
Participant O	Male	N/A	Bachelor's	12	5	Large
Participant P	Male	31	Doctorate	10	0.5	Large
Participant Q	Female	30	Master's	9	8	Large
Participant R	Male	57	Master's	38	8	Large
Participant S	Male	32	Master's	9	7	Large
Participant T	Male	55	Master's	25	7	Large
Participant U	Male	37	Master's	12	6	Large
Participant V	Female	47	Master's	20	5	Medium
Participant W	Male	29	Bachelor's	2	3	Small
Participant Y	Female	47	Master's	12	20	Large
Participant X	Male	25	Bachelor's	3	1	Small

2.3.2 Data collection

A semi-structured interview protocol was iteratively developed based on relevant literature. The purpose of the interview was to elicit concrete stories of experiences that practitioners had using prototypes to engage stakeholders during front-end design activities. The structure of the interview was guided by best practices in protocol development [85,86]. We piloted the protocol with 11 participants (different from the 22 participants in our study) to gain familiarity with the protocol and refine questions as per recommended practice [86].

At the start of the interview, we provided participants with definitions for front-end design, products, prototypes, and stakeholders. Defining these terms supported participants in sharing experiences that aligned with our research goals and potentially expanded what they

chose to share with us, given that our definitions were intentionally broad. The definitions we used in the interviews were informed by existing literature. The definitions and sources that supported our definitions are included in Table 3.

Table 3 Key definitions used in the interview protocol.

Term	Definition provided during the interview	Source
Front-end Design	"Phases of product development associated with problem identification/needs finding, problem definition (e.g., requirements and specifications development), background research, concept generation, early prototyping, and concept selection."	Adapted from [9,10,111]
Product	"The designed artifact. The prototype could represent a process (the procedure), a system, or a sub-part of the designed artifact."	Adapted from [24,35]
Prototypes	"Include mock ups, CAD models, drawings, scenarios, and other representations of the product or its use."	Adapted from [24,28,35]
Stakeholders	"Anyone who will affect or be affected by the artifact at some point, including end-users, colleagues, manufacturers, clients, policy makers/ministry officials, technicians, procurement officers, etc."	Adapted from [97,111]

The interview questions prompted participants to focus on a specific past design project that involved the use of prototypes to engage stakeholders during the front end of design. The practice of contextualizing interview questions in the participants' experiences supports the collection of authentic responses and rich descriptions [85]. Follow-up questions were asked to gather additional details specific to each participant's experience [86]. Example questions from the interview protocol are listed in Table 4.

Table 4 Interview protocol themes and sample questions.

Themes	***Example Questions***
Project specific	● Can you select a project that you would say is the best example of a project you worked on where you used prototypes in the design front-end to engage stakeholders?
Types of prototypes	● Who were the stakeholders you engaged during your project? ● How did you choose which type of prototype to make to engage with stakeholders?
Stakeholder interactions	● Can you tell me how you used these prototypes to engage with different stakeholders? Could you describe the interactions in more detail?
Design activities	● Can you tell us about a time when engaging stakeholders with prototypes led to a better understanding of the need? ● Could you focus on a requirement that was informed by the use of a prototype with a stakeholder? ● How was using prototypes to engage stakeholders more relevant in one design activity than in others?
Generalizing across projects	● When you think across all of your projects during which you have used prototyping during the front end to interact with stakeholders, would you say your strategy changed depending on the design activity for which you are using the prototype? How? Can you give me an example? ● What determines whether the approach will be mostly serial or mostly parallel across projects? When does that change?

2.3.3 Data analysis

Audio-recordings of the 22 interviews were transcribed, verified against the audio recordings for accuracy, and de-identified. Initial analysis was conducted by two members of our research team; each person read the collection of transcripts and documented emergent themes and associated data representing prototyping strategies for engaging stakeholders during the design front end.

The process of identifying strategies was inductive. Themes were identified by finding an action in the data which involved a stakeholder being engaged with a prototype in the context of a project's front-end design activities. Literature that was used in the development of the interview protocol was consulted when refining theme names and definitions.

Two members of our research team performed the initial analysis and iterated on the collection of strategies comparing the identified strategies to one another and the corresponding original data in the transcripts, which aligned with the method of constant comparison [87,88]. A

final list of prototyping strategies, with their definitions and examples, was created and served as the codebook for the rest of the analysis process.

To represent the prevalence of a strategy within the data set, full transcripts were selected as the unit of analysis. Each transcript was analyzed to determine which of the identified strategies listed in the codebook were used by each participant. Two members of our research team independently coded two full transcripts. With the coded transcripts, inter-rater agreement was calculated by taking the total number of agreements for all the strategies per transcript (out of 17 possible) and dividing by the total number of agreements and disagreements per transcript. The resulting inter-rater agreement was 88%, which is considered strong [129]. The remaining 20 transcripts were divided between the two researchers for coding. Both coders reviewed one another's coded excerpts for each strategy in each transcript, and all disagreements that emerged from this review process were resolved until full consensus was reached. During this process, code definitions were minimally refined to ensure clarity, specificity, and agreement among our research team members.

The reported frequency for a given strategy indicated how many transcripts showed evidence of that particular strategy. While we analyzed for frequency, we did not interpret it as an indicator of greater or lesser importance of any prototyping strategy.

2.4 Findings

Seventeen prototyping strategies for stakeholder engagement during the design front end were identified in the interviews with medical device design practitioners. Participants sometimes leveraged single strategies, and sometimes used multiple strategies concurrently, examples of which can be seen in some of the interview excerpts. None of the strategies were evident in all of the participants' shared experiences, and most of the strategies were used by less

than half of the participants. The strategies, their definitions, and example excerpts from the interview data are included in Table 5. The sub-sections that follow examine the most and least commonly described strategies, and a subset of strategies which are expanded upon because of their richness and relationship with existing literature beyond engineering design practice.

2.4.1 Most cited strategies across participants

Show the stakeholder multiple prototypes concurrently

Seventeen of the 22 participants described the strategy of showing stakeholders multiple prototypes during an engagement. Participants described a variety of reasons for bringing more than one prototype to a front-end design engagement, including to help stakeholders articulate feedback, make comparisons across diverse concepts and features, and to communicate the incomplete status of the design project, i.e., that stakeholders had an opportunity to contribute to future design iterations.

Some participants showed stakeholders multiple prototypes to assess whether a clear need existed in a particular design space and to clarify the need. For example, Participant D showed stakeholders multiple prototypes that focused on different potential stakeholder needs in a specific geographic region:

> *"We had those three prototypes, and we went to [the country] and visited a number of hospitals with [community partner]. we were showing multiple prototypes and talking about multiple topics, and really trying to gauge. Is there a need here that's not being filled currently that something like this could fill?"*

Table 5 Strategies for stakeholder engagement using prototypes during the front end of design.[2]

Strategy	Definition	*Example Interview Excerpts*	n
Show the stakeholder multiple prototypes concurrently	Prompt the stakeholder to compare options using multiple prototypes of different needs, concepts, features, form factors, requirements, or engineering specifications.	*"They have 30 of [those prototypes] sitting on the table in front of [the stakeholders]. They pick it up, and they spend about half a second on the ones they don't like. "Nope, I hate that," and then throw it down. Then they pick up the one they do like, and they'll sit with it for a minute just oohing and aahing over it. Sometimes that level of feedback is like, just the amount of time that they're holding it tells you as much as anything else..." (Participant O)*	17
Brief the stakeholder about the project and the prototype(s) shown	Introduce the stakeholder to the project, describe the prototype(s), including defining its purpose and current form and fidelity, and describe expectations of the stakeholder's participation.	*"What I tended to do is introduce the problem, state why we were there, and then pull out the prototype, show some specific aspects that we are looking for feedback" (Participant F)*	16
Observe the stakeholder interacting with the prototype(s)	Prompt the stakeholder to interact with prototypes while observing the interaction.	*"Sometimes, when you give [stakeholders] prototypes, they use it completely differently, and then that becomes human factor input. Even though the session was not created as a human factor session, you get some valuable input by observing." (Participant P)*	15
Show a single prototype to the stakeholder	Engage the stakeholder using one prototype.	*"Given our limited resources, most of the major stuff was done linearly and a single prototype iteration" (Participant A)*	12
Show the stakeholder supplemental materials related to the concept to complement the prototype	Engage the stakeholder using storyboards, test data, computational models, materials, physical models, etc. to elaborate on the details of the prototype.	*"...we would send the picture of the [prototype components], the design, front, back, side view, we were sending the raw materials. So we would actually have a swatch booklet, so we would have just like little swatches of the raw materials that were going into the [product] so that people could touch and feel them to provide feedback..." (Participant H)*	11
Introduce the prototype(s) to the stakeholder in the use environment	Place the prototype in its environment of use when engaging the stakeholder.	*"We gave them the working prototype, and they took it to their health clinic, and they [said] 'Okay, we could keep it here. We could go like this. We could do like that.' They did like a dry run of how this product would be used in their context of use. That's in person, in context." (Participant E)*	11
Have the stakeholder interact with the prototype(s) in a simulated use case	Replicate relevant conditions of the product's environment of use in a simulated setting where the stakeholder interacts with the prototype(s).	*"We used simulation mannequins and the simulation, the [program name] at the hospital a lot when we'd meet with like users so that they could try it out… Because you can look at something and kind of know, but until you try it out and use it in a mannequin you don't really know. So, we did pick the setting of them being able to be as true to how they would normally do the procedure." (Participant N)*	11
Polish the prototype(s) shown to the stakeholder	Create or modify a prototype to show to the stakeholder that more closely resembles the final form of the concept versus the current status of the project.	*"So when I am trying to put something out in the field, I'm trying to get it as finished as possible even just aesthetically. If I need to spray paint it or something [because] people will look at a 3D print and be like, "why is it this color?" Well it's like, it can be any color, it doesn't matter that's just the color that the 3D printer had in it at the time... if I'm going to stakeholders outside of the office, I don't want them to get distracted on those types of questions. I want to get to the heart of it as quickly as possible..." (Participant A)*	9

[2] Counts (n) refer to the number of transcripts with the strategy.

Encourage the stakeholder to envision use cases while interacting with the prototype(s)	Prompt the stakeholder to imagine how they would use the prototype in use cases.	*"You're going to have to… start probing 'consider when you're using the distal... grip and you're doing a [type of procedure]. Tell me about it. What about this gets in your way? What about this is problematic for you? Consider that use case and tell me about this…'" (Participant O)*	7
Reveal only relevant information to the stakeholder specific to the prototype or its use	Strategically reveal relevant information, leaving out details about the prototype(s), such as functionality, or rationale behind design decisions	*"We would brief them about the product we were hoping to test with them, what we were trying to test or what we were trying to see, but we would also try to do it in a way where we didn't tell them what outcome we wanted... we might say "we want to test to see how this product supports you around your [limb] while you [do this activity]". We wouldn't tell them, "we're looking to see specifically if you have pain on your [specific body part] when you [do this activity] or to see if you're uncomfortable when you [do this other activity]." (Participant W)*	7
Task the stakeholder with creating or changing the prototype(s)	Prompt the stakeholder to create or modify the prototype(s) by physically altering prototypes, writing or drawing ideas. In this strategy, the stakeholder, rather than the practitioner, makes or changes the prototype(s).	*"We had the big alpha prototype we would give them these supplies and say what would be all the functions that you'd want to see in a device? And we kind of talked through that. So it's like on and off buttons, you want multiple settings of intense and less intense […]. We would bring out these pieces and ask them, okay take your favorite on button and display and so forth, can you tell us where on the device you want these things to go?" (Participant F)*	6
Prompt the stakeholder to select prototypes and prototype features	Ask the stakeholder to choose or prioritize ideas based on provided prototypes.	*"They sort of rotated doctors and nurses through a whole bunch of stations, and one of the stations was looking at these different devices and getting feedback and ranking which one they liked the best and what qualities they want in a device." (Participant D)*	6
Standardize the refinement of prototypes shown concurrently to the stakeholder	Present prototypes that are at the same level of refinement (fidelity, functionality, and finish) when shown simultaneously to the stakeholder.	*"I would try to have the prototypes [be] as similar to each other as possible so that you don't have something [with] very bright colors and very attractive and some lower [quality prototypes]." (Participant P)*	6
Present a deliberate subset of prototypes to the stakeholder	Present fewer, carefully selected prototypes to the stakeholder than the full set of prototypes created.	*"You don't want to have 20 different concepts, and sometimes certain concepts are still similar and it's really confusing and you don't get as much information out of it as you want." (Participant P)*	6
Modify the prototype(s) in real time while engaging the stakeholder	Make changes to the prototype(s) while the stakeholder is present. In this strategy, practitioner rather than the stakeholder, makes the changes to the prototype(s).	*"We were out to a user discussing one of these prototypes, […] and they didn't like it. We got out our modeling clay and said, let's take this and do something different. Do you like this?" ...You're changing stuff on-the-fly when it's appropriate." (Participant G)*	5
Make prototype extremes to show the stakeholder	Exaggerate prototype characteristics that represent a feature at a specification's upper or lower limit, or represent opposite characteristics.	*"The main question that we really had to answer was does this need to actually have liquid in it or does it have to be dry? And half of our stakeholders told us one thing and half told the other, so we said okay, let's make two very different prototypes. One is going to be wet. One is going to be dry. And just kind of show them and let them try and see in the end, what did they end up using." (Participant K)*	4
Lessen a prototype's refinement when showing it to the stakeholder	Engage the stakeholder with less sophisticated and/or complete prototype(s) than the current project status.	*"If we were trying to get a function, something that just conveys the motion, or the actuation of something, there are actually times where we will intentionally choose a less refined method of prototyping […] and almost like not whittling, but close. There's actually some times where that's valuable, because it helps set the tone of the session that something is really early phase." (Participant U)*	4

Participants also had stakeholders interact with multiple prototypes to help determine what features might be part of a given solution. For example, Participant V provided stakeholders multiple parts they could connect together when discussing potential solutions for a feature:

> *"For [a device] . there were a lot of different ways that you could attach [parts] . we actually used a 3D printer and printed the parts and then we had different ways that you could snap pieces together and different ways in which you could attach [them] . We brought [them] in and had nurses put it together . and give us feedback."*

Participants also used multiple prototypes with stakeholders to translate requirements to engineering specifications. For example, Participant N created prototypes that represented different variants of potential solutions' sub-systems:

> *"We had two different materials, two different rigidities for the main [component] of it and we had two different flexibilities of the [sub-component] and so we did all the combinations and put them all down on the table and had [the stakeholders] try each one multiple times without saying anything about [them]. They were just A, B, C, and D. And then let them interact them with it without pre-biasing them saying, this one's stiffer, that one's more flexible . we definitely put them in a setting where it was all there at once . so that we can really compare what's a noticeable difference, what's not a noticeable difference, what's desirable, what's not . So just understanding [a product requirement].*

You just don't know until you're trying it . it's not something anybody can throw a number at, they have to feel it."

Brief the stakeholder about the project and the prototype(s) shown

Sixteen participants discussed the importance of the introductory remarks of the engagement session for building rapport, conveying goals, and managing stakeholders' expectations. Participants described using prototypes to assist with conveying the goals of the front-end engagement and the status of the solution concept(s). For example, Participant T described the use of this strategy to elicit feedback about a design's intended functionality during an early stage of his team's design process:

> *"[We tried] to show the functionality but also emphasize that we didn't have a form factor and we were a long way from the right form factor or final design ..The feedback wasn't things like this is too big, or this doesn't seem very reliable, or this handle isn't ergonomic, or any of those kinds of things. We were much earlier and these prototypes didn't address any of those issues, so we tried to set expectations. Where are we at? At a high level we tried to set the expectations of where we were at so that the prototypes were viewed appropriately, and we could get the right type of input on that we were looking for in that stage."*

In another example of this strategy, Participant N prepared stakeholders to engage with a prototype by telling them to pay attention to a specific aspect of the prototype and asking them to disregard other aspects of the design:

> *"We frequently would introduce it to them with, this is what we're trying to figure out, to focus them on one aspect of it. So I guess you could consider that a strategy where we tried to kind of prep them for, this is what you're going to see and ignore these things. This is similar to how it will be, this is not similar to how it will be. And, we want to know this. to get them tuned into exactly what we're looking for."*

Observe the stakeholder interacting with the prototype(s)

Fifteen participants described the strategy of observing stakeholders interact with a prototype. Encouraging stakeholders to interact with prototypes provided participants with information about requirements, unexpected behaviors, design shortcomings, and usability issues. For example, Participant F described observing a stakeholder place a component of a prototype in an unexpected direction, that led to a subsequent design modification:

> *"On one of our early prototypes ... people would try twisting [the component] the opposite way [we had intended], and they would get stuck, and then you'd see them go the other way, or they'd put the [component] backwards, and so they'd have to put it back in, and [we made] a lot of feature adjustments based on very, very early observations."*

Participants also discussed observing stakeholders' silent reactions, including stakeholders' unspoken emotional reactions when interacting with a prototype. Participant T

described these unspoken reactions as complementary feedback that may otherwise not be articulated by the stakeholder during the session:

> *"[We] observe that their hand is slipping, or see that they are having to turn a handle say fifty times and it looks like they are annoyed by that, but they don't necessarily say, oh, I'm turning the handle too much. You need to change this."*

2.4.2 Least-cited strategies across participants

Modify the prototype(s) in real time while engaging the stakeholder

Five of the 22 participants described the strategy of modifying the prototype(s) during the engagement session. Modifications of prototypes were prompted by stakeholder feedback, but implemented by the designers during the engagement session. Participants noted that the use of this strategy generated particularly rich stakeholder feedback because stakeholders perceived that they were actively contributing to the development of a potential solution by physically manipulating the prototype that they were being prompted to assess.

Participant K described an engagement session during which the team was focused on understanding how stakeholders defined "comfort" within the context of the ideas presented:

> *"[There was] this [prototype] that was developed and a lot of [the session] was . sitting there and sewing and changing one thing and having [the stakeholder] try it and then sewing. Just trying it out and having a variety of options. A lot of that is, that was a project that was going to be worn. It had to be comfortable. It had to have requirements that were much more ergonomic."*

Participant G described the importance of being able to quickly modify the prototype based on the stakeholder's response in order to obtain real-time feedback about the modified design:

> *"We were out [talking] to a user discussing one of these prototypes . and they didn't like it. We got out our modeling clay and said, let's take this and do something different. Do you like this? You're changing stuff on-the-fly when it's appropriate."*

Make prototype extremes to show the stakeholder

Four participants discussed the practice of showing stakeholders prototype extremes to inform the development of requirements and the translation of requirements to quantifiable specifications. Additionally, this strategy helped participants to resolve conflicting feedback.

Participant R discussed the use of a prototype during the design front end to gather information about weight-related extremes:

> *"It was [a] non-functional [prototype], but the idea was to try to figure out how heavy it could be, so I made different sized weights, and you could put it in there, and you kept getting bigger and heavier until you say, what's too heavy? If it's too small you take it out and say, is this too light? So that was just a design to determine [the] limits on the weight of the device."*

Participant K described using prototypes that represented opposing ideas of a requirement to help his team resolve variable and inconsistent stakeholder feedback:

> *"I was working on a project [where] the main question . was does this need to actually have liquid in it or does it have to be dry? And half of our stakeholders told us one thing and half told the other, so we said okay, let's make two very different prototypes. One is going to be wet. One is going to be dry. And just kind of show them and let them try and see in the end, what did they end up using because I think sometimes you have an idea of what you want but then there is that practicalities of actually doing it in real life."*

Lessen a prototype's refinement when showing it to the stakeholder

Four participants described de-emphasizing the design team's investment in an idea by showing less sophisticated versions of prototypes to stakeholders than prototypes that fully captured the current design iteration or stage of the project. This approach was pursued because participants perceived that stakeholders were more comfortable giving honest feedback if the stakeholders perceived that the design was still a work in progress, i.e., stakeholders might be hesitant to critique a design that could not be changed. For instance, Participant N mentioned the use of a hand-drawn sketch of a previously generated CAD model to promote more candid stakeholder feedback:

> *"We did some ... sketching on a paper. I know it doesn't sound like a prototype but the purpose of that is that the more raw it looked, the more input we got. Because if it looked finished, people would just say, oh, yeah, yeah, that's good. And they'd be afraid to*

offend you. to give their input because they thought it was done. So, sometimes we just tried kind of pencil and paper. like not even printed out from CAD. Like, just redraw what I had in CAD with pencil and paper because then people would give me more, like, oh, she's early on, I can go ahead and give my input, you know."

Participant T described stripping prototypes of non-defining features or showing crude versions of the features to communicate that these features were not the focus of the engagement session:

"Say... a handle was needed [for the prototype] to be functional and ergonomic, but the handle itself wasn't really a defining feature. It might have no handle, or a crude handle, [otherwise.] sometimes, there is a distraction. "Like, why is this handle so big? Or why is this handle not operating smoothly?" Or things like that. I use the handle analogy a lot. Instead of putting a handle on, maybe pliers or grippers on the end that are actuating it, because you don't care about the form factor, you care about the functionality and how it may make it easier to be reliable."

2.4.3 Additional strategies representing diversity of prototyping strategies cited across participants

While Table 5 includes a description and example for each of the strategies revealed in this study, in this section, we provide additional data associated with three particular strategies to further highlight the diversity of strategies uncovered in the sample and some of the important nuances among the strategies.

Polish the prototype(s) shown to the stakeholder

Nine of the 22 participants described experiences during which they took additional steps to refine prototypes, rather than show unpolished prototypes to certain stakeholder groups. Participants claimed that this strategy helped certain stakeholder groups focus on the goals of the session rather than being distracted by the appearance of unfinished prototypes, in contrast to the strategy "*Lessen a prototype's refinement when showing it to the stakeholder*." Participants mentioned they often "polished" the appearance of the prototypes to leave a good impression with stakeholders from whom they needed buy-in.

Participant R used polished prototypes to avoid comments about a prototype's unfinished look:

> *"The other thing we did to get them past the, that's horrible and disgusting, is we made a lot of. models that were non-functional that looked pretty. Some of them even had LEDs on them. It's crazy I know, but it's true. One of the guys on our team. would make pictures that looked like it was actually real. actual rendering, 3D graphics rendering of prototypes, and we made some for [this stakeholder group] as well. It looked pretty but they didn't do a darn thing, they were just a hunk of metal and plastic, right? That helped too, to be honest, having pretty stuff. For the non-technical [stakeholders], pretty stuff helps."*

Participant C elaborated on making a positive impression with the first presentation of a prototype to a potential user:

"…the prototype had one big electronic chip. If [somehow] something like that is being put on [the user], [the caregiver] will be scared. So, we made sure that the prototype, the enclosure of the prototype, is something that doesn't seem as a danger to the [user]. it had to look appealing so the [caregiver] accepted it, because the first impression of anything comes from the first look at an object."

Task the stakeholder with creating or changing the prototype(s)

Six participants talked about encouraging stakeholders to make modifications to a prototype themselves as a way to better understand stakeholders' thoughts and concerns. In contrast to *"Modify the prototype(s) in real time while engaging the stakeholder,"* where the practitioners were modifying the prototype, stakeholders were prompted to be the main actors and make changes to the prototypes.

Participant U described a session when he instructed stakeholders to directly alter the prototype:

"We also said, okay, here's a pile of 3D printed parts, with bits and pieces of the other ones, how would you arrange them in a way that would be easiest, or most logical, or straight forward, or intuitive to use . We decided that for the build-a-handle exercise, it was more about relative location, and access to the features, than it was picking things based on aesthetic, or tactile feedback . We gave them modeling clay to stick it on there, just stick it where you want it, and then have them actually go through the activity of holding it in their hand, or laying it on the table, and using it . seeing if the way that they put it together was appealing or not. There were a lot of cases where they started out,

and they sort of arranged things in a way that was aesthetically pleasing, but then when we went through the mock procedure, they realized that things were in the wrong location. That it looked nice, but there was no way that you could get to something, or things just kind of got in the way, and it was cumbersome. Which is really what we were after."

In this example, Participant U used two strategies: "*Task the stakeholder with creating or changing the prototype(s)*" and "*Encourage the stakeholder to envision use cases while interacting with the prototype(s),*" i.e., stakeholders were asked to arrange parts and act out how they would use the prototype.

Introduce the prototype(s) to the stakeholder in the use environment

Eleven participants described introducing the prototype within the intended environment of use. Participants who employed this strategy either asked stakeholders to use the prototype or envision the use of the prototype while being in the use environment, as opposed to in an environment unrelated to its use. In the following example, Participant D described how stakeholders were able to provide feedback that informed sizing and use, by introducing the prototype within its use environment:

" [The stakeholders] instantly wanted to put [the prototype] and actually try it out in the NICU, where it would actually go. Whereas if we hadn't had anything physical ..., I think that topic may not have come up and we might not have realized where they wanted to set it and so forth. So being able to size it correctly [...] if we didn't have that cot hanging

around, they may not have even thought to mention that. Even if we asked, "Where would you put it in the NICU?" And they might have said, 'Oh, I guess we'll put it on a table or maybe in one of the cots,' the idea of them picking it up and actually seeing if it fits or questioning whether it would fit, that probably wouldn't have even come up."

2.5 Discussion

2.5.1 Comparing study findings to the literature

In this study, we identified 17 strategies that medical device design practitioners employed to engage stakeholders with prototypes during front-end design activities. While the strategies had similarities, they were each distinct. For example, *"Task the stakeholder with creating or changing the prototype(s)"* and *"Modify the prototype(s) in real time while engaging the stakeholder"* are similar in that both require altering a prototype, but distinct with respect to who the main actor is in performing those changes (design practitioner or stakeholder). This specificity across the collection of strategies extends the prior literature that describes prototype uses. Further, the collection of strategies emphasizes the roles that prototypes can have in front-end design beyond those traditionally emphasized in engineering design textbooks, such as for representing products in evolving detail and specificity [24,25]. While prior literature highlights uses of prototypes for supporting stakeholder involvement and eliciting requirements (e.g., [46]), the strategies revealed through this study (and the associated rich transcript excerpts) describe nuanced approaches regarding how to plan and execute front-end stakeholder engagements with prototypes.

The findings also revealed that design practitioners intentionally leveraged these particular strategies with prototypes to engage stakeholders; they believed their choices had

specific benefits related to their project goals at the time. The design practitioners in our study articulated their intentional prototyping choices during the planning and execution phases of their stakeholder engagements and routinely used prototypes strategically as intermediate representations of their design work—as probes for promoting meaningful dialogue and gathering information to develop requirements and specifications as well as to evaluate early solution ideas. Related work demonstrated intentional strategy choices among medical device design practitioners when engaging stakeholders with prototypes during the design front end; specifically, practitioners selected prototypes based on who they were engaging with and in which environment the engagement occurred [130,131].

The strategies discovered bring attention to particular aspects of stakeholder engagements with prototypes. Some strategies focused on how many prototypes to show the stakeholder, other strategies focused on decisions about the quality of the prototypes shown, and still others focused on how to engage the stakeholder with the prototype, including what to tell the stakeholder, what activities to facilitate, and where to perform the engagement. We discuss strategies that demonstrate these different foci in the following paragraphs.

Although we have chosen quantity, quality, engagement, and environment as groupings for exploring these front-end prototyping strategies for engaging stakeholders, we note that there are several other ways in which the strategies might be grouped.

Examples of strategies that brought focus to prototype quantity were *"Show the stakeholder multiple prototypes concurrently"* and *"Show a single prototype to the stakeholder."* The prominence of the use of multiple prototypes across practitioners in our study could, in part, be a reflection of the ongoing exploration inherent to front-end design processes. However, participants explained other reasons for their choices. Practitioners who showed stakeholders

multiple prototypes concurrently felt that the approach enabled stakeholders to compare design alternatives, convey tangibly that design ideas were still being explored, and encouraged stakeholders' input.

Contrastingly, some participants in our study, at times, also showed stakeholders a single prototype and explained how context, design stage, specific engagement goals, and resource constraints, such as cost and time, sometimes prompted their decision to employ this approach. An analogous trade-off was reported in Moe et al. [38], which described that cost, schedule, and performance priorities drove the quantity of prototypes and iterations made, but this study was not front end or stakeholder engagement focused.

Decisions about prototype quantity depended on multiple factors for participants in our study, which was also documented in our related work [132]. Our study differs from prior work by shifting the focus from determining the number of prototypes based on a product development timeline [31] or suggesting that multiple prototypes in parallel are typically beneficial [30,133,134] to deciding prototype quantity based on stakeholder engagement goals. A universal recommendation on prototyping quantity misses an opportunity to leverage the value that each strategy might bring in different situations.

An example of a strategy that focused on the quality of the prototype was *"Lessen a prototype's refinement when showing it to the stakeholder."* Participants expressed that they purposely invested time and effort into developing lesser-refined prototypes than the most-up-to-date representations of concept solutions to communicate to stakeholders that there were still opportunities for their input to influence design outcomes. As prototypes tend to evolve along with a design process, it was surprising to find that designers lessened the refinement of their prototypes to fulfill specific goals for stakeholder engagement during the design front end. In the

case of practitioners in our study who used this strategy, they invested time to create less polished versions of prototypes, while existing literature recommends low-fidelity prototypes because they are quick and inexpensive to make [13]. Existing literature also highlights low-fidelity prototyping as supporting iteration and progress [84], informing ideation and concept development [23], exploring basic assumptions, and understanding user mental models [34], reasons that aligned with practitioners' rationales in our study for the strategy to lessen the refinement of prototypes.

In contrast to the previous strategy, there were times participants showed prototypes that were intentionally made to look more refined than the actual state of the design ideas, evidenced by the strategy *"Polish the prototype(s) shown to the stakeholder."* Participants claimed the strategy was a way to help eliminate distractions and move stakeholder's thinking past the prototype's appearance. The literature provides mixed recommendations with regards to the impact of more or less "polished" versions of prototypes in terms of fidelity, finish, and aesthetics. For example, making prototypes to be aesthetically pleasing has been shown to produce more positive judgments by users in both low and high fidelity versions than with low aesthetic prototypes [125], but more finished sketches have been shown to be better regarded by stakeholders than their rougher counterparts [135]. In contrast, another study found that cross-cultural medical device design stakeholders provided responses with greater variation, less design input, and less rationale when presented with low-fidelity prototypes (sketches and cardboard models) than when presented with more refined prototypes (CAD models and 3D printed prototypes) [47]. Considering that both polishing the appearance and lessening the refinement of a prototype were found as strategies, our findings are most consistent with Tiong et al. [34], who suggested that when using higher fidelity prototypes, these should match the

specificity of the design questions being posed. For example, when asking a stakeholder to evaluate overall concepts, too detailed a prototype could distract and bring attention to smaller features instead of the overall functioning of the device.

An example of a prototyping strategy that focused on engagement activities was *"Brief the stakeholder about the project and the prototype(s) shown."* Participants in our study perceived that the prototypes could have an unintended role in the interaction if left unexplained, such as distracting the stakeholders. Furthermore, to yield quality information, participants indicated they felt the strategy supported rapport building, which aligns with literature describing building trust as an important stakeholder engagement technique [66]. This briefing strategy was one that contributed to a larger goal of preparing stakeholders to successfully engage in the session, an idea discussed further in related work by [136]. Reasons participants used this strategy (e.g., to communicate objectives of the engagement, build rapport, and manage expectations about the prototypes to be shown) are consistent with the usability testing literature that describes the value of telling stakeholders what they are about to see, how they should interact with the prototypes, and what is expected from them during usability testing [137].

Other examples of engagement-focused strategies included: *"Modify the prototype(s) in real time while engaging the stakeholder"* and *"Task the stakeholder with creating or changing the prototype(s)."* In the former strategy, the designer made the design changes, and in the latter, the stakeholder had the more active role. This contrast aligns with a spectrum of participation where stakeholders can be either subjects of study or co-creative partners [102,122,138]. *"Modify the prototype(s) in real time while engaging the stakeholder"* aligns with literature describing "live prototyping," which is used by designers to build and alter prototypes while engaging stakeholders [77]. On the other hand, *"Task the stakeholder with creating or changing*

the prototype(s)" aligns with the focus of participatory workshops, though participants in this study seldom described intentional planning of such workshops. While practitioners in our study engaged stakeholders, they did not describe the level of participation that characterizes participatory design approaches [138]. This observation could partly be explained by the medical device design context in which participants were working. The objectives of a design team embedded within organizations in a competitive business landscape might not always be aligned with the objectives of participatory methods and co-design.

An example of a strategy focused on the environments for stakeholder engagement with prototypes during the front end was *"Introduce the prototype(s) to the stakeholder in the use environment."* Participants in our study, when possible, situated stakeholders in settings to yield more authentic information than in settings separated from the environments in which the intended designs would be used. This finding is consistent with principles of contextual design, which promote that prototypes, even low fidelity ones, need to be tested in the stakeholders' actual use contexts and that the prototypes need to support the stakeholders' current tasks to elicit useful knowledge [4]. Human factors literature supports that human performance is closely associated with the environment where the tasks and behaviors occur [139]. However, being in the actual environment of use was not always an option, and as an alternative, practitioners used other strategies that helped stakeholders connect to the environment, such as *"Have the stakeholder interact with the prototype(s) in a simulated use case,"* and *"Encourage the stakeholder to envision use cases while interacting with the prototype(s)."* These two strategies reveal the value practitioners placed on the environment in which the design would be embedded, and when they could not situate the engagement in the actual environment, they sought ways to connect the stakeholders to it.

The prevalence of some of the most commonly used strategies described in the study might be domain-specific to medical devices. For example, the Food and Drug Administration [140] provides recommendations for designers to ensure safe and effective device use and two of the recommendations focus on user interactions and use environments. Two frequently mentioned strategies from our findings related to user interactions *("Observe the stakeholder interacting with the prototype(s)"* (n = 15) and *"Encourage the stakeholder to envision use cases while interacting with the prototype(s)" (n = 7)*) may have emerged in a large number of transcripts because of their potential roles in supporting the early identification of use-related risks. Similarly, frequently used strategies related to use environments *("Introduce the prototype(s) to the stakeholder in the use environment"* (n = 11) and *"Have the stakeholder interact with the prototype(s) in a simulated use case*" (n = 11)) may have facilitated the recognition of potential risks associated with device usage in particular settings. While the prevalence of the strategies may be impacted by the medical device context, the strategies align with existing design approaches described in the design of products beyond medical devices, such as assistive technology, power tools, and consumer electronics, among other physical products [24].

2.5.2 Limitations

One limitation of the study is that participants could have blurred the lines between front-end and back-end prototyping uses for stakeholder engagement. We worked to limit the impact of this limitation by defining front-end design phases at the onset of the interviews, probing for specific examples within early design activities, and excluding back-end strategies as best as possible during analysis. However, the highly iterative nature of design could have resulted in participants sharing strategies that stretched beyond solely front-end activities that we were not

able to clearly exclude during analysis. A related limitation is that because we excluded strategies that appeared to be within back-end activities, some of the front-end strategy counts could potentially be lower than participants' actual use within the experiences they shared because of the caution we employed in borderline examples.

Another limitation is that the strategies counted were based on participants' ability to recall their past experiences. We did not observe the strategies in use as they occurred, but rather relied on participants' descriptions of their experiences.

The study is limited in knowledge of the extent to which medical device design practitioners' prototyping strategies during the design front end are representative of front-end processes in other domains. The study's focus was on rich descriptions that can support transferability to other design domains. However, the strategies identified in this work are limited to the practitioners of medical device design included in our study.

The study is also limited in that most participants worked in the United States, therefore primarily reflecting design practices within that region of the world. Additionally, race and ethnicity questions were not included in the study questionnaire, limiting our knowledge on these aspects of diversity across participants.

2.5.3 Implications

The findings of this study can impact how medical device design practitioners approach their work. Specifically, the findings bring focus to the ways that designers in this domain can engage stakeholders using prototypes within early design work, facilitating awareness of the breadth of strategies that can be considered. Increasing the awareness of strategies used by others can encourage practitioners to build their repertoire and more explicitly support their choices of prototyping strategies to engage stakeholders in front-end design activities.

Beyond medical device design, other domains can benefit from the articulation of strategies that emerged in our findings. While our study did not focus on domains outside of medical devices, many of the strategies we found have commonalities with more general strategies in the broader design literature, suggesting that these strategies are worth considering for use by practitioners in other domains. Within the engineering design literature, there are limited compilations of suggested strategies with the level of specificity in our findings as well as with a focus on prototyping with stakeholders during front-end design. Thus, the collection of strategies in our findings serve as a resource for practitioners to consider as they make design and prototyping choices, allowing them to perhaps consider a greater number of potential strategies than they had considered previously. Further, this collection of strategies can encourage practitioners to articulate why they do or do not consider a strategy useful in their domain, and be more intentional in their prototyping choices for stakeholder engagement in the design front end.

In addition to their potential uses by practitioners, the collection of strategies and associated examples from our findings can also be leveraged as educational and training resources for novice and early career designers. As research has shown that engineering novice designers have limited conceptualizations of prototypes [26], especially their application in the front end [35], and struggle in general to know how to engage with stakeholders [116,141], training and pedagogy that leverages the examples revealed in our study could support designers in expanding their use of prototypes during the front end of design to engage stakeholders.

More intentional strategy choices and a broader repertoire of design strategies can ultimately support more successful design outcomes. As the strategies were used by practitioners in our study to better meet the needs of stakeholders, other practitioners may leverage them in their own work, and may be more successful in understanding their stakeholders as they make

design decisions. Because stakeholder engagement has been linked to design quality [3,9], the use of these strategies may improve the prevalence and quality of stakeholder engagement during early design work.

2.6 Conclusion

Strategies for engaging stakeholders using prototypes during the front end of design have not been documented extensively in the engineering design literature, and existing strategies in engineering design texts lack a focus on front-end work as well as rich detail for how and when particular prototyping strategies may be most useful. Our study identified 17 prototyping strategies that medical device design practitioners intentionally used to engage stakeholders during early design phases. These findings can be used to expand the awareness and repertoire of strategies that practicing engineering and novice designers can leverage. These prototyping strategies can support engineering designers in intentionally facilitating communication and collaboration with stakeholders, eliciting meaningful and detailed information from stakeholders, supporting different levels of stakeholder participation and integration in design processes, and ultimately, having more comprehensive, well-informed, and successful front-end design work.

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Chapter 3 Prototyping Strategies to Engage Stakeholders During Front-End Design: A Study Across Three Design Domains[3]

Abstract

Using prototypes to engage stakeholders during front-end design activities is crucial for successful design outcomes that are grounded in real stakeholder needs and priorities. Compared to prototyping that is used for iterative refinement during back-end engineering design activities, prototyping that informs problem definition, requirements and specifications development, concept generation, and other front-end design activities is understudied. To identify patterns in prototyping strategies for engaging stakeholders during the design front-end, we conducted semi-structured interviews with 26 design practitioners across three product design domains: automotive, consumer products, and medical devices. Seventeen strategies evident across the collection of practitioners were used in generally consistent ways, with some variation based on context, e.g., project scope, stakeholders engaged, and the stakeholder interaction situation. Twelve out of the 17 strategies were used by industry practitioners across the three domains, and five of the 17 strategies were used by practitioners from the medical device domain and either the automotive or consumer products domain. The descriptions and examples in context of prototyping strategies used to engage stakeholders during front-end design can guide the design strategies of both experienced and novice designers.

[3] This chapter was co-authored with Grace Burleson, Shanna Daly, and Kathleen Sienko.

3.1 Introduction

The use of prototypes with stakeholders during the early, front-end design stages is among the most crucial activities conducive to a product's commercial success in the market [7], which hinges on appropriately defining and addressing stakeholder needs. Engaging stakeholders around a shared medium, such as a prototype, helps designers and stakeholders discuss values and priorities by enabling feedback and facilitating effective communication [14,15]. However, prototyping within engineering design curricula tends to emphasize back-end activities; for example, many engineering design textbooks position prototyping as a stage rather than an ongoing activity that can co-exist with problem definition, requirements and specifications development, and concept generation (e.g., [24,25]). Even though back-end design prototyping is essential for testing design performance or how a specific design meets specifications once these have been established [30], back-end design activities are unlike the front end of design. During the front end of design, problems, opportunities, requirements, specifications, and ideas are emergent and still being defined [142]. These complex, ambiguous, and iterative design activities can be deeply informed and guided by using prototypes, including and specifically for stakeholder engagement.

Some literature has described both general and specific strategies that can be used to engage stakeholders with prototypes; some of these strategies are intended to be broad strategies that span a design process or back-end design-specific strategies (e.g., [34,100,105,143,144]), while limited literature has been dedicated to prototyping strategies specifically associated with the front end of design (e.g., [145,146]). Some design research has considered how prototyping for stakeholder engagement is influenced by the stakeholder(s) engaged and questions asked with the prototype [47], the designers' prior knowledge of the design space, and the product's degree

of user interaction [40]. Additionally, while not specific to prototypes, research has shown that product type, product domain, and company structure may shape the types of stakeholders who designers include in their design processes and to what level the stakeholders are involved [106]. Organizational characteristics might further shape stakeholder engagement with prototypes as well. For example, research shows that organizations may prioritize stakeholder engagement if their intended design outcome will have a high degree of user interaction, or if the organization is developing a radical design [11]. In mature organizations or product lines, design is often approached more incrementally, with gradual, cumulative changes made to existing products [147]; thus, these organizations might decide they do not require as much external stakeholder engagement. Designers also may approach prototyping decisions based on what has been described as different "cultures of prototyping" referring to explicit organizational structures and implicit processes. [148]. These cultures, per [148], may tend to prototyping-driven specification development, i.e., prototypes are used iteratively, treated as experiments, or specification-driven prototype development, i.e., prototypes are treated as an "end product of thought."

Some recommended prototyping approaches might apply across multiple contexts; for example, some studies have found commonalities in prototyping approaches while sampling across a variety of contexts (e.g., [14,35,149]). However, the extent to which prototyping strategies—particularly for front-end uses of prototyping strategies with stakeholders—are used across disciplinary domains is unknown, as are nuances of how these strategies are leveraged to align with the context. Thus, this study aimed to investigate prototyping strategies used to engage stakeholders during the design front-end of three product domains (automotive, consumer products, and medical devices), and to describe patterns and distinctions in strategies used across designers' specific project contexts.

3.2 Background

Prototyping strategies in engineering design literature have been defined as "a set of choices that dictate actions" in a broader product development process [31]. Prior research centered on prototyping strategies has primarily focused on the specific techniques to produce prototypes for specific applications within certain phases within a product development project [40]. Such planning may include using specific techniques to achieve specific objectives [30,45]. For example, in some prototyping efforts it may be appropriate to employ the technique of isolating subsystems for the objective or reducing total time [30]. While other research has emphasized a prototyping strategy containing decisions about prototyping media, materials, manufacturing, tests, and iterations decisions throughout a development process [29]. However, relative to refinement and iteration of developed ideas represented by prototypes, prototyping strategies to engage stakeholders remain understudied, particularly during the earliest phases of design. Importantly, engaging stakeholders with prototypes early in design processes has been attributed to project and organizational success [13,150].

3.2.1 Prototyping Strategies for Stakeholder Engagement in Engineering Design

Several studies have explored the role of prototypes to support communication with stakeholders in engineering design [15,20]. Research has shown how different prototype characteristics impact the information gathered [46], in addition to how the stakeholders' background and type of questions they are asked impacts the feedback they give on prototypes [47]. Theory that describes the dynamic ways in which prototypes influence social interactions have been established [14,15,109,151], but it lacks actionable strategies to engage stakeholders with prototypes. Further work is needed to achieve the same level of specificity in prototyping strategies to engage stakeholders as those that focus on the artifact itself.

To that end, prior work has identified strategies that designers in the medical device field leverage to engage with stakeholders during front-end stages [131,146]. An interview-based research study [146] that sampled medical device design practitioners working in corporate and global health settings described 17 strategies consisting of intentional uses of prototypes to engage with stakeholders during the front-end of design. These strategies described nuanced approaches to carrying out front-end stakeholder engagements with prototypes in ways that prompted meaningful dialogue and helped practitioners gather information to develop requirements and specifications as well as to evaluate early solution ideas. Further work demonstrated that practitioners working in global health settings adapted their use of the same strategies from the broader sample depending on the context of their projects [131]. For instance, some practitioners adapted strategies to tackle stakeholder remoteness, gather context-specific requirements, and bridge cultural gaps between them and the stakeholders they engaged. While these practitioners spanned various design contexts in the medical device field, the extent to which these strategies translate to other product design domains and contexts remains unexplored.

3.2.2 Prototyping across different dimensions of context

While there are commonalities in product development processes shared across contexts, there are also differences based on the unique context of the organization performing the design work and the specific design project challenges [24]. The concept of "prototyping culture"—an organization’s structures and processes involving common media used for prototypes, traditional methods to create prototypes, and styles to manage prototyping [148]—is anchored on a similar idea that multiple aspects and dimensions of context have an impact on design outcomes. Using different companies as cases, Schrage [148] argued that several factors influence and are

influenced by the prototyping culture: (1) the way companies manage the relationship between specifications development and prototype development, (2) the prototype media and fabrication methods, (3) the question types and shared vocabulary that prototypes enable (4) the speed of prototyping cycles, and (5) who gets to partake in prototyping (e.g., designers, customers, suppliers).

In other work, Jensen et al. [46], described relationships among prototype functionality, stakeholder involvement, and requirements elicitation, and suggest that the designers' organizational cultures around prototyping can support or hinder the ability to uncover latent requirements and needs. Further, Elverum et al. [40] outlined contextual factors that could impact the use of prototyping strategies, such as prior knowledge and experience of the designers in the problem area, how predictable the use context is, and anticipated level of user interaction. Two projects from their sample had vastly different levels of prior knowledge in the problem area, use context predictability, and level of user interaction which led them to vastly different strategies that still lead to good outcomes, i.e., the project with greater prior knowledge had a more focused, mainly digital, and less resource-intensive prototyping approaches.

Specifically, how prototyping strategies are leveraged based on such contextual factors, especially as they pertain to the choice and use of prototyping strategies to engage stakeholders, remains to be explored. Similarly, as decisions about strategies to use prototypes depend on many aspects of the context, approaches to the front-end of design can vary according to context. For example, product radicalness, target customers, the core team's experience, and the team's leadership have all been found to be important aspects of context influencing how the design front end is carried out across company contexts [11]. While general prototyping recommended practices may be consistent across many project examples, these studies suggest that the extent

to which the strategies are used and the detailed nuances in how they are leveraged may vary according to context.

3.3 Methods

Prior research identified 17 prototyping strategies that global health and multinational medical device design practitioners used to engage stakeholders during front-end design phases [146]. The goal of this study was to investigate the transferability and applicability of these prototyping strategies to other design domains and to compare prototyping strategies used to engage stakeholders during front-end design across the design domains of medical devices, automotive and consumer products. This study was guided by the following research question: What prototyping strategies do design practitioners use to engage stakeholders during the front-end of design?

3.3.1 Participants

The The participants in this study included 26 design practitioners from three design domains: automotive (n=7), consumer products (n=7), and medical devices (n=12). The medical devices participant subset included practitioners working in multinational companies and startups to represent industrial contexts consistent with the other two design domains included in this study. As such, while broader sample from which the prototyping strategies originated included global health design practitioners they were not part of this study. Eligible participants were required to (1) have worked in a design role (e.g., technology, product design, design research, engineering design), (2) have worked in the design of mechanical and/or electromechanical products or systems, and (3) have a front-end project example that they could discuss from one of three industry sectors: automotive, consumer products, or medical devices.

The research team used several techniques to identify and recruit eligible participants, including leveraging the study team's existing professional networks and university offices with established academia-industry partnerships and posting recruitment material on social media (e.g., LinkedIn groups). Potential participants voluntarily expressed their interest via an online recruitment questionnaire, which the research team used to screen for eligibility. Eligible participants were contacted by the study team to confirm interest, clarify questions, and schedule an interview time. Participants were compensated for their participation.

The University of Michigan Institutional Review Board deemed this study as exempt and all participants provided written consent to participate in the study. Participant information is summarized in Table 6.

Table 6 Participant information.[4]

ID	Product and company type	Design Exp. (years)	Job Tenure (years)	Sex	Ethnicity	Education	Age
AU1	Vehicle performance sub-system, large manufacturer	6	2	F	Hispanic/Latin X	Master's	29
AU2	Vehicle performance sub-component, large manufacturer	26	NP	M	NP	Master's	50
AU3	Full system build, supplier	2	2	M	White	Master's	34
AU4	Vehicle interiors, large manufacturer	4	0.4	M	White	Master's	27
AU6	Vehicle sub-system, supplier	4	2	M	Asian	Master's	30

[4]Note: (AU = Automotive; CP = Consumer products; MD = Medical devices) Ethnicity data were not collected for the medical device domain participants (noted by "NC"), and other participants chose not provide their ethnicity (noted by "NP").

ID	Product and company type	Design Exp. (years)	Job Tenure (years)	Sex	Ethnicity	Education	Age
AU7	Vehicle exteriors, large manufacturer	4	2	M	Asian	Master's	27
AU8	Full system layout, large manufacturer	2	2	M	Asian	Master's	25
CP1	Sports equipment, large manufacturer	35	29	M	Hispanic/ LatinX	Bachelor's	59
CP2	Product packaging, household, and personal care products, large manufacturer	35	5	M	NP	Master's	62
CP3	Product packaging, large manufacturer	29	4	M	White	Master's	50
CP4	User experience innovation, consulting firm	10	1	F	White	Master's	33
CP5	Household and personal care products, large manufacturer	25	25	F	Hispanic/ Latinx	Master's	50
CP6	Household products, small to medium enterprise	4	1	M	Hispanic/ Latinx	Bachelor's	26
CP7	Household products, small to medium enterprise	6	2	M	White	Master's	34
MD1	Intubation device, startup	6	6	F	NC	Doctorate	37
MD2	Surgical device, large manufacturer	12	5	M	NC	Bachelor's	34

ID	Product and company type	Design Exp. (years)	Job Tenure (years)	Sex	Ethnicity	Education	Age
MD3	General hospital equipment, large manufacturer	10	0.5	M	NC	Doctorate	31
MD4	Imaging system sub-component, large manufacturer	9	8	F	NC	Master's	30
MD5	Surgical device, large manufacturer	38	8	M	NC	Master's	57
MD6	Imaging system sub-component, large manufacturer	9	7	M	NC	Master's	32
MD7	Cath lab & cardiac surgery devices, large manufacturer	25	7	M	NC	Master's	55
MD8	Cath lab & cardiac surgery devices, large manufacturer	12	6	M	NC	Master's	37
MD9	Infusion device and hospital equipment, consulting firm	20	5	F	NC	Master's	47
MD10	Orthopedic device, startup	2	3	M	NC	Bachelor's	29
MD11	Cath lab device, startup	3	1	M	NC	Bachelor's	25
MD12	Implantable devices, large manufacturer	12	20	F	NC	Master's	47

3.3.2 Data Collection

We leveraged a semi-structured interviewing approach to collect data about participants' experiences engaging stakeholders with prototypes during front-end work to collect rich and nuanced information. The medical device design practitioners were interviewed first as part of

another study with a larger sample of medical device designers, including multinational medical device design practitioners and global health design practitioners [146]. Then, minimal changes to the original protocol were made to refine some questions for clarity based on those interviews. Additionally, minor changes to the protocol were made following pilot studies with three individuals with consumer products and automotive project experience to facilitate transferability of the interview questions to these domains. Examples of changes included adding a question that asked participants to briefly describe their background and work in their industry, as well as adapting terms so they translated across domains.

Definitions of terminology and concepts used throughout the interview such as front-end design, product, prototypes, and stakeholders were provided at the beginning of the interview. The interviewer asked each participant about a past design project during which they used prototypes to engage stakeholders during the front end of design. Follow-up questions prompted participants to share further details characterizing their experiences. The goal of each interview was to identify specific prototyping strategies, gain an understanding of the practitioners' experiences using prototypes to engage with stakeholders, and assess what was involved in planning and facilitating these stakeholder engagements. Example questions from the protocol are included in Appendix A.

Most of the interviews were conducted via video conferencing software (n=23); three interviews conducted were in person. All interviews were audio recorded. On average, interviews lasted 79 minutes.

3.3.3 Data analysis

All interviews were transcribed and de-identified, totaling 2056 minutes (approximately 34 hours) and 416 pages for data analysis. Then, transcribed interviews were revised by a study

team member to ensure accuracy between the audio files and transcripts. For the first part of the analysis, all transcripts were read in-depth to identify and annotate instances of strategies, which we defined as the intentional actions practitioners used to engage a stakeholder or stakeholders using prototypes during the front-end of design, across different projects and project contexts. We deductively analyzed according to an existing codebook from prior work (Table 7) as well as inductively analyzed for any additional strategies that emerged beyond the ones already in the existing codebook. Deductive analysis is a useful technique for the application and extension of existing theories, frameworks, and assumptions [89,90], thus the technique was deemed appropriate for assessing the transferability of the prototyping strategies used by medical device designers to those used by automotive and consumer product design practitioners. Inductive analysis is a useful technique for finding dominant or salient themes in the raw data [90] and was appropriate for seeking strategies beyond the ones identified previously. Using a full transcript as the unit of analysis, two study team members, with previous qualitative data analysis experience, determined the presence or absence each previously identified strategy as well as marked any potential additional strategies throughout the interview transcript.

Coding was performed first independently, comparing intermediate results, and discussing among the full research team through an iterative process. At this point, inter-coder agreement between two coders was calculated using a proportional agreement method: taking the number of agreements divided by the number of agreements and disagreements. Agreement was 71% across seven transcripts. Disagreements were resolved through discussion in those seven transcripts. Additionally, we found that the sources of these disagreements primarily consisted of deciding when a strategy was used intentionally (e.g., observe versus simply witnessing), as well as strategies that shared some degree of similarity such as “Encourage the stakeholder to

envision use cases while interacting with the prototype(s)" and "Have the stakeholder interact with the prototype(s) in a simulated use case." As disagreements were resolved, we clarified these aspects of coding. Then, coding for strategies was performed by a single coder. We then tabulated how many participants in each domain described leveraging each prototyping strategy during their interviews.

Table 7 Codebook used for data analysis as defined in prior work [146]

Strategy	Definition
Brief the stakeholder about the project and the prototype(s) shown	Introduce the stakeholder to the project, describe the prototype(s), including defining its purpose and current form and fidelity, and describe expectations of the stakeholder's participation.
Encourage the stakeholder to envision use cases while interacting with the prototype(s)	Prompt the stakeholder to imagine how they would use the prototype in use cases.
Have the stakeholder interact with the prototype(s) in a simulated use case	Replicate relevant conditions of the product's environment of use in a simulated setting where the stakeholder interacts with the prototype(s).
Introduce the prototype(s) to the stakeholder in the use environment	Place the prototype in its environment of use when engaging the stakeholder.
Lessen a prototype's refinement when showing it to the stakeholder	Engage the stakeholder with less sophisticated and/or complete prototype(s) than the current project status.
Make prototype extremes to show the stakeholder	Exaggerate prototype characteristics that represent a feature at a specification's upper or lower limit, or represent opposite characteristics.
Modify the prototype(s) in real time while engaging the stakeholder	Make changes to the prototype(s) while the stakeholder is present. In this strategy, the practitioner rather than the stakeholder, makes the changes to the prototype(s).
Observe the stakeholder interacting with the prototype(s)	Prompt the stakeholder to interact with prototypes while observing the interaction.
Polish the prototype(s) shown to the stakeholder	Create or modify a prototype to show to the stakeholder that more closely resembles the final form of the concept versus the current status of the project.

Present a deliberate subset of prototypes to the stakeholder	Present fewer, carefully selected prototypes to the stakeholder than the full set of prototypes created.
Prompt the stakeholder to select prototypes and prototype features	Ask the stakeholder to choose or prioritize ideas based on provided prototypes.
Reveal only relevant information to the stakeholder specific to the prototype or its use	Strategically reveal relevant information, leaving out details about the prototype(s), such as functionality, or rationale behind design decisions
Show a single prototype to the stakeholder	Engage the stakeholder using one prototype.
Show the stakeholder multiple prototypes concurrently	Prompt the stakeholder to compare options using multiple prototypes of different needs, concepts, features, form factors, requirements, or engineering specifications.
Show the stakeholder supplemental materials related to the concept to complement the prototype	Engage the stakeholder using storyboards, test data, computational models, materials, physical models, etc. to elaborate on the details of the prototype.
Standardize the refinement of prototypes shown concurrently to the stakeholder	Present prototypes that are at the same level of refinement (fidelity, functionality, and finish) when shown simultaneously to the stakeholder.
Task the stakeholder with creating or changing the prototype(s)	Prompt the stakeholder to create or modify the prototype(s) by physically altering prototypes, writing or drawing ideas. In this strategy, the stakeholder, rather than the practitioner, makes or changes the prototype(s).

For the next phase of analysis, all coded strategy excerpts were analyzed to describe information about the prototyping strategy *use scenario*, which included information about the setting, stakeholders, project goals, participants' rationales or any other unique trait of the situation that characterized details about the strategy use. An example of an excerpt that described a use scenario surrounding the use of the prototyping strategies "Show the stakeholder multiple prototypes concurrently" and "Have the stakeholder interact with the prototype(s) in a simulated use case" is provided here:

"There was another project I was working on around the same time that was also supposed to go to a customer clinic that we were looking at building different concepts of basically one design. And that was also really important to kind of show people. But a part of it is you need to convey to people that there might be some costs associated with certain designs. So you could ask somebody if they want something and they would say yes, but when they actually are in the car and realize the shortcomings of you have less leg room or something like that if you do this, which is maybe something that's not readily apparent if you look at it on a piece of paper. Having that kind of information fed back to the customer in a really tangible [way] is really important."

The use scenario for this excerpt from an automotive industry participant was summarized as having a focus on using the multiple prototypes in the simulated setting to demonstrate the trade-offs or compromises in other parts of the system that were associated with each of those designs. After all coded strategy excerpts from all transcripts were reviewed for information about the use scenario, the use scenarios were sorted thematically within each strategy code.

3.4 Findings

The findings are structured in three main parts. The first part consists of participants' strategies across domains. Then, we elaborate on different strategy use scenarios applied by participants. Lastly, we describe instances of strategic uses of prototypes to engage stakeholders that differed from the existing set of 17 strategies from prior work [146] that was used for analysis.

3.4.1 Prototyping strategies design practitioners used to engage stakeholders during the front end of design

Our findings showed that all 17 previously identified strategies for engaging stakeholders with prototypes during the design front end were used by at least one participant in our study sample regardless of domain. Participants from the automotive and consumer products domains in this study described using 12 of the 17 stakeholders. Five of the 17 strategies were used by participants from two of the three domains: automotive and medical devices participants used three of the five strategies, while consumer products and medical devices participants used two of the five strategies. We summarize these frequencies by strategy and participant domain in Table 8.

Table 8 Prototyping strategy usage counts by domain (unit of analysis: participants).

Strategy	**AU (n=7)**	**CP (n=7)**	**MD (n=12)**	**Total (N=26)**
Show the stakeholder multiple prototypes concurrently	6	5	8	19
Brief the stakeholder about the project and the prototype(s) shown	6	3	7	16
Show the stakeholder supplemental materials related to the concept to complement the prototype	4	4	8	16
Observe the stakeholder interacting with the prototype(s)	1	5	8	14
Show a single prototype to the stakeholder	6	3	4	13
Have the stakeholder interact with the prototype(s) in a simulated use case	5	2	6	13
Introduce the prototype(s) to the stakeholder in the use environment	1	4	5	10
Polish the prototype(s) shown to the stakeholder	3	1	6	10
Prompt the stakeholder to select prototypes and prototype features	1	4	2	7
Standardize the refinement of prototypes shown concurrently to the stakeholder	1	2	4	7
Task the stakeholder with creating or changing the prototype(s)	1	3	2	6

Strategy	**AU (n=7)**	**CP (n=7)**	**MD (n=12)**	**Total (N=26)**
Encourage the stakeholder to envision use cases while interacting with the prototype(s)	1	1	4	6
Reveal only relevant information to the stakeholder specific to the prototype or its use	2	0	4	6
Present a deliberate subset of prototypes to the stakeholder	3	0	3	6
Lessen a prototype's refinement when showing it to the stakeholder	1	0	4	5
Modify the prototype(s) in real time while engaging the stakeholder	0	2	2	4
Make prototype extremes to show the stakeholder	0	1	3	4

Participants from particular domains described the use of specific strategies for the projects shared with different frequencies compared to the participants in other domains. For example, a greater proportion of automotive industry participants described using the following strategies than participants from the other two domains: *Show the stakeholder multiple prototypes concurrently; Brief the stakeholder about the project and the prototype(s) shown; Show a single prototype to the stakeholder; Have the stakeholder interact with the prototype(s) in a simulated use case*; and *Present a deliberate subset of prototypes to the stakeholder*. Participants from the consumer products industry discussed using the following strategies more often than participants from the other two domains: *Observe the stakeholder interacting with the prototype(s); Introduce the prototype(s) to the stakeholder in the use environment; Prompt the stakeholder to select prototypes and prototype features; Task the stakeholder with creating or changing the prototype(s);* and *Modify the prototype(s) in real time while engaging the stakeholder*. Participants from the medical devices domain described the use of the following strategies more often than participants from the other two domains: *Show the stakeholder*

supplemental materials related to the concept to complement the prototype, Polish the prototype(s) shown to the stakeholder, Standardize the refinement of prototypes shown concurrently to the stakeholder, Encourage the stakeholder to envision use cases while interacting with the prototype(s), Make prototype extremes to show the stakeholder, Reveal only relevant information to the stakeholder specific to the prototype or its use, and Lessen a prototype's refinement when showing it to the stakeholder. Further, participants discussed how their project contexts, which included the domain of work, impacted their choices when using prototypes with stakeholders.

Strategies with Similarities in Use Scenarios Across Domains

In addition to the use of particular strategies, our findings also showed similarities in the *use scenarios* of the strategies across domains, i.e., how the strategies were leveraged to advance practitioners' goals. This sub-section contains three strategies with exemplary participant excerpts to describe their use scenarios.

Brief the stakeholder about the project and the prototype(s) shown was similarly

The strategy *Brief the stakeholder about the project and the prototype(s) shown* was similarly leveraged by eight participants across domains to establish expectations for participation and engagement with stakeholders when showing prototypes, build rapport, and share the purpose of the session. For participants from the automotive domain, this use scenario involved a supplier-stakeholder, while for participants from the other two domains, the use scenario involved users.

For the same strategy, another use scenario that emerged from seven participants across the three domains centered on contextualizing the prototype so it could be seen or evaluated as intended, which was more specific and connected to the prototype than the prior use scenario

about situating the session. When participants engaged with users and customers, they prefaced interactions by communicating the early nature of their design processes to emphasize the opportunity for actionable input from stakeholders and by framing completely new and unfamiliar designs. One example was participant CP2, who worked on a project to develop novel packaging for a consumer product to improve prospective users' interactions with the product. He described the use of a prototype to introduce a new design concept to the stakeholder's home, and described how the stakeholder interacted with the prototype:

> *"We [are] explaining what it is before [the consumer] uses it. So because it's not anything she's ever seen before […] you have to provide context. And people would say to me, "why are you explaining it? Shouldn't you test if [the prototype is] intuitive?" I [say], we will get to intuitive. First, we [have] to [figure out] does [it get her] attention and can she make it work when we explain it to her. Then we'll figure out how to make it the affordances such that she just naturally knows how to use it." (CP2)*

Participants from the automotive domain who engaged stakeholders from system or sub-system teams outside of their own design teams, such as clients, discussed requirements and features at a technical level through the strategy *Brief the stakeholder about the project and the prototype(s) shown*. For instance, participant AU6, who worked for a supplier, developed a specific type of component for a vehicle sub-system for vehicle manufacturer clients. At project onset he had a list of specifications from the client. AU6 described an engagement with a client during which the team presented the initial design concept:

> *"...the initial design concept will be presented to [the client] through this 3D model... This [is] kind of an interactive session will go on and a lot of design inputs will be acquired through these sessions. So, in these kinds of sessions, actually we are developing the design concept. ... So, when we go with such kind of design concept, we will have to explain every minute detail, we will have to go [into] the every minute detail of the design, how it is, how it will work. ..." (AU6)*

Show the stakeholder supplemental materials related to the concept to complement the prototype

The second strategy used similarly across scenarios was *Show the stakeholder supplemental materials related to the concept to complement the prototype*, which also had some similarities in its use scenarios across domains. One use scenario for this strategy consistently described by participants across domains was presenting an idea or concept using different representations of the same overarching concept to convey it fully and elaborate on the details of a prototype. This use scenario applied to various stakeholders, including users, consumers, and clients (as described by participants) and included sets of prototypes with differing levels of detail or refinement, 2D and 3D prototypes, distinct prototypes for demonstrated form and function, physical prototypes accompanied by presentation slides or sketches and drawings, among others. AU3 summarized the numerous possible combinations by stating, "every single toolbox, every single option for exchanging ideas."

In a different use scenario of *Show the stakeholder supplemental materials related to the concept to complement the prototype*, participants from consumer products and medical devices domains described using the strategy to convey a specific concept by combining materials, tools, or other analogous artifacts in the absence of a functional prototype, particularly with user

stakeholders familiar with the associated procedure or workflow. In contrast with the previously highlighted use scenario, this use scenario did not involve functional, demonstrable, or highly integrated prototypes. For example, participant CP3, who in this specific excerpt described a customer-facing packaging project involving a combination of prototypes that individually conveyed appearance, interaction, and function to the stakeholder:

> *"Then we've used a lot of sketches of stuff, but what I try and do if I have a sketch is I kind of do a looks like, feels like works [like]. So I do a combination of prototypes. If I had a sketch and we did that with some of the packaging that we did with [the products], I had concept boards that not only had a sketch of the prototype, it had a little bit of story boarding which showed how it functioned." (CP3)*

In yet another use scenario for *Show the stakeholder supplemental materials related to the concept to complement the prototype*, participants from the consumer products and medical devices domains presented design alternatives through prototypes and supporting evidence or data for the prototype being shared. The stakeholders engaged in these scenarios were typically managers or decision-makers during a design review or a go/no go decision. For example, participant CP5 described how she engaged decision-makers within her company using prototypes of a household item and supplementary consumer data when making a pitch for an early investment to perform a pilot test with one of the company's suppliers:

> *"If you are early in the stage of the process, and if you are just in the investigative and then hypothesis testing, it's going to be as simple as, "This is the data that I have. This is*

the solution. I do not know yet, but I do believe that this is what's going to happen." And I can just give you an example specifically on [a household product]. So we weren't sure if we needed to invest capital equipment on the top because our original proposal was to actually just launch [a type of container], like your typical [complementary product], literally like a big tub of [the complementary product], where you had the top where consumers just pick up [another complementary product] and put it on there. And we needed to engage with stakeholders to see if they could enable us to do a pilot testing with one of the top suppliers. Well, obviously that requires money, right? So to help them make the decision, yay or nay, then we needed to create that prototype. And then I had to create some videos to show them how the end users would be interacting with both solutions, and try to capture the reactions, and then provide the data of what are the good things and the bad things for both of solutions. And based on that ... And again, I'm not the decision maker. My job is to provide information, to provide data with examples, with prototypes, so then the decision makers can say yay or nay…" (CP5)

Have the stakeholder interact with the prototype(s) in a simulated use case

Lastly, the strategy *Have the stakeholder interact with the prototype(s) in a simulated use case* had some similar use scenarios across participants from all three domains. Six participants across domains described recreating aspects of the use context and broadly exploring near-realistic user behaviors with the prototypes. For example, users or customers could interact with prototypes in a simulated retail environment for consumer product prototypes, in a replicated hospital or emergency room environment for medical device prototypes, or the simulated interior of a vehicle for automotive prototypes. Participant AU4 shared an example of a project during

which he used prototypes within a simulated environment to convey the interior of a vehicle. When using this strategy, he also simulated emotions associated with interacting with the vehicle's buttons during an emergency situation:

> *"For the one project I was working on mainly that I was just discussing, a lot of it was around basically putting people in a vehicle without telling them anything about it and getting them to use the prototypes to conduct like normal operations, like putting the car in drive and driving it away or putting it in a parking spot. But we were also looking at things like what would somebody do in an emergency panic situation? What button would they press? How would they press it? Would they know what to do if you told them what button to press in the panic situation versus not telling them? So trying to put people through different scenarios and understand what scenarios people would use the controls. Understanding how people understood the controls and in what context they would use those." (AU4)*

Participants from the automotive and medical device domains also described projects involving a different use scenario for *Have the stakeholder interact with the prototype(s) in a simulated use case*. Instead of broadly exploring user behaviors, participants described employing physical and virtual tools to establish adequate context to enable them to understand design challenges, design decisions, and requirements with the use of a prototype. For instance, Participant AU2 discussed embedding a digital prototype in its intended environment to introduce an incremental design change for a vehicle prior to building complex digital models or simulations in order to seek input from a decision-making stakeholder:

"That data is light, and quick, and can be controlled such that some basic functionality in the representing the actual end product, but all it's not heavy enough to do all of the simulations that are required. So, in this case, you may have the stakeholder like the product owner and the engineer, the high-level stakeholders of, "Hey this is what we want. Is this going to meet your expectations?" And you may be looking at it in a virtual setting, projected on the screen, or you may be collaborating in the virtual space and virtual reality, and you're, visually seeing together this concept that was rendered on a piece of paper. Now it's digitized and you can immerse it in an environment to say, "Yes, that's going to meet my expectation ...""" (AU2)

Strategies with Varying Use Scenarios by Domains

Our findings also revealed differences among *use scenarios* for a subset of strategies by domain. While the strategy *Prompt the stakeholder to select prototypes and prototype features* was described by participants from each domain, its distinct use scenarios did not overlap among the projects described by the participants across the three domains studied.

Three participants from the consumer products domain and one participant from the medical devices domain prompted stakeholders to consider existing objects in their homes or places of work as prototypes. For example, Participant CP4 used a card-sorting exercise with user-stakeholders to sort features among existing solutions twice: first, they sorted features based on desirability and then on likely benefits. The aims of this prototype engagement activity were to confirm known needs and explore new needs:

I had a card sort activity. There's actually also two axes, … on the vertical axis … I think the card sort was about benefits that products could give ... Some benefits were benefits that already exist in [existing] solutions, others were maybe new to the world. And we also had cards that were blank, so people could add their own. … The vertical axis was like, from the top to the bottom, which of these are most desirable to you? So which benefits do you … most want your […] products to deliver to your clothing? And then once they were organized vertically and they could be tiered, they could be on the same level, then I had them move them either to the left or to the right. To the right was, the products I had already used already deliver this benefit to my clothing and then to the left was my products failed to deliver this benefit. And so then we use that quadrant of most desired, but not currently fulfilled benefit to then go into a co-creation activity. (CP4)

In a different use scenario three participants from the consumer products domain and one participant form the automotive domain tasked stakeholders with prioritizing prototypes, and later analyzed patterns that emerged. In contrast to the previous use scenario, here stakeholders were prompted to pick a favorite, which was a choice that informed the practitioner about what benefits stakeholders' cared about. For example, Participant CP3 described a project involving clothing. In this example, she recruited members of a sports team as user-stakeholders and embedded multiple prototypes in their use context. Then, following intensive interactions with the prototypes over an extended period of time, she prompted the stakeholders to select one of the prototypes to keep:

"I recruited a rugby team who were training a lot. It was the summer and I said they needed to wear that [clothing item] every day when they were working out but they couldn't wash it in between. And we kept a diary and tried to see did they actually see this […] benefit. And then if they did at the end we took it away from them and then we asked them if they wanted one of the [clothing items] back which one would they take..." (CP3)

In yet another use scenario for *Prompt the stakeholder to select prototypes and prototype features*, two participants from the automotive and medical devices domains used prototypes to prompt decisions from decision-makers (e.g., upper-management stakeholders) instead of user-stakeholders. For instance, Participant AU7 described a meeting during which his design team used prototypes to obtain direction or approval from decision-making stakeholders regarding an incremental change to a vehicle sub-system:

"But the outcome that we expect from those meetings is usually a decision. Either it's approval or getting their direction on where we want to go, at least let's say if we have two different prototypes or two different designs. We are actually asking the management on which direction they want us to go to. And that helps most of the time, having a prototype. [...] Most of the time, the stakeholder, as I said, is not a peer, but it's the upper management. Usually, it's a yes or no. Or it's either go with this design or that design." (AU7)

3.4.2 Strategic uses of prototypes with stakeholders in relationship to predefined strategies

Two participants each articulated a front-end prototyping strategy for stakeholder engagement that they had used but did not completely align with the existing strategies as they

were previously defined. The first strategy was described in an experience by Participant CP2. He described the use of a strategy that partially aligned with *Introduce the prototype(s) to the stakeholder in the use environment* and *Make prototype extremes to show the stakeholder*. In this example, Participant CP2 engaged with the stakeholder in the environment of use and explored extremes, but the stakeholder was asked to use objects within their home as prototypes versus being provided with prototypes:

> *"We go, "Show us a package you love, show us a package you hate, show us a package that's easy, show us a package that's hard, show us a package that's clean, show us a package that's messy." And it doesn't have to be a [specific product] package. Any package. ... And so, we said, "And one that's beautiful." And so, this woman here… you could see how beautiful the finishes are in her house. It's still quite a small space, … But her finishes are gorgeous. … And so, we were saying, "A package that's beautiful." And over in this corner right here, you can see that, right there, is the Remy St-Martin bottle on display. And then, she pulled it down for us to get a look at. So this is a Remy St-Martin cognac bottle. All right? Now, she has an empty liquor bottle on display in her tiny apartment. What does that say is possible with packages? If you do it right, you can make it worthy of display. … Now, would it be as worthy of display as Remy St-Martin cognac? Probably not. Can we move the [user] experience in that direction? Probably." (CP2)*

The second strategy was described by CP4, who was touring a user's home while playing the role of the prototype:

"... we had set it up, said, first you're going to take us on a tour of your house as if we are an article of clothing. And so, all right, you've just bought me. What do you do first? Some people don't do anything, but some people have like a pretreatment. So they would take us to that part of the house and show us like, "Oh, well, I go outside to my backyard to spray it with this anti-stain thing." I don't know. And then we would end up in their closets and when we're in their closets, I had to pack post its. And every time they pulled out something that was important to them, like, oh, I love this pair of jeans, but I can't get it from stretching out. So I was like, all right, stretched out jeans is something I've now written out in the post it, "Oh, I love this pair of shoes, but they get scuffed up too easily." Okay, I've written the pair of shoes." (CP4)

Consistent with the other example, Participant CP4 represented the design idea in a manner not fully captured by the original set of strategies. In this example, Participants CP4's strategy most closely aligned with *Introduce the prototype(s) to the stakeholder in the use environment.* However, a prototype was not made or provided by the designer.

3.5 Discussion

In this study, we found that the previously identified prototyping strategies used to engage stakeholders during front-end design, to a great extent, were used across projects from all three design domains, suggesting transferability across the domains studied. This finding was not entirely unexpected given that aspects of professional design practice span domains, including design reasoning patterns [152,153] and other overarching themes that characterize design tasks and design problem spaces [92].

Some strategies were salient in practitioners' projects within certain design domains. The strategies used among a greater proportion of automotive industry participants compared to the other two domains could be used with a diverse set of stakeholders as opposed to primarily customers and users. When we examined these participants' projects, despite being described as early, front-end design examples, most appeared less open-ended. In contrast, many of the strategies described by the majority of the consumer products participants were notably suitable for use with users and consumers.

While the use of strategies was generally consistent, there were nuanced variations in terms of how participants applied each strategy. The findings described strategies that exemplified some of these variations. Variations among the use scenarios were noted among projects from participants within the same domain, but also among projects from participants across domains. Most strategies were applied in a similar fashion among projects across all domains. This finding is consistent with prior work that describes generalizations across design processes [91], and the influence of project and design task context on modifications of design processes and methods including the type of stakeholders engaged and designer's unique perspectives and prior experience [17,154,155]. Further, previous research has demonstrated that design practitioners adapt methods in an opportunistic manner to serve their unique design goals [155]. It is therefore not surprising that front-end prototyping strategies used to support stakeholder engagement will vary based on context as some prototyping literature has also highlighted some contextual considerations impacting prototyping choices [15,40,47,131].

Further, the additional participant excerpts that did not fully align with the strategies as initially defined in the codebook may indicate the fluid and changing nature of front-end design tasks, as well as the dynamic nature of prototypes in social situations. Many objects can become

and be used as a prototype when prototypes are defined broadly [28], a concept that is more broadly accepted in participatory design processes and co-design than in engineering.

In summary, our findings showed that strategies used to engage stakeholders with prototypes during the front end of design were applicable to multiple product domains, which suggests that the strategies might be transferable beyond the initial domain of investigation, i.e., medical device design. These findings also suggest design practitioners with diverse project characteristics adapted their use of methods to engage stakeholders using prototypes during front-end design activities.

This study's contributions have several implications for design practice, education, and research. One implication for practice is that designers across multiple product domains can leverage these strategies in their work, supported by the descriptions in this paper, including examples of how the strategies were used across domains and in some specific use scenarios. As previous work has shown that practitioners sometimes seek to learn from peer experiences in addition to descriptions of pure methods [155], the ways we share these strategies in this paper can allow practitioners to see ways that other designers engage stakeholders with prototypes during early design work.

The presented strategies can be leveraged for design education of students or novice practitioners. A focus on specific methods that can inform education on stakeholder engagement and prototype use during the front end of design in design education and early training aligns with literature claims of engineering work where more scaffolding might be needed, including leveraging prototyping practices deliberately [19,35], engaging stakeholders with prototypes [156], and navigating complex or conflicting stakeholder information during front-end design activities [116].

An implication of our work for design research is the investigation of broader conceptualizations of prototypes and their uses for stakeholder engagement to begin shedding light into processes that support or hinder problem definition, requirements and specifications development, and early concept exploration activities in engineering design. In the past, design research on prototyping has centered on the design intent represented in prototypes defined by various verifiable characteristics. While this is important work, our findings illustrated practitioners' prototyping approaches to shape stakeholder interactions with prototypes during the earlies stages of design. We posit that how designers frame and intentionally guide stakeholder engagements with prototypes might require a broader view of prototyping in engineering design research than what it has traditionally encompassed, especially when examining the front end of design when prototype characteristics (e.g., form, function, fidelity) may be more fluid than in back-end stages and many aspects of the design context and the stakeholder interactions shape the outcomes of stakeholder engagements as more recent work has in part presented, e.g., [15].

Limitations of this study include the potential blurring of prototype-related activities with stakeholders associated with the early versus late stages of a design project. In order to focus practitioner descriptions on front-end design work, we carefully screened participants prior to enrolling them in the study and provided participants with a clear definition of front-end design activities. However, as participants described their experiences, they may have explained details of their prototype use that moved into more back-end phases of work.

Also, our study focused on three specific product design domains, thus we are limited in knowing to what extent these strategies transfer to other design domains beyond those that we studied.

Finally, we were limited in the diversity of participant racial and ethnic backgrounds, as not every background was represented among the study participants. Further, race and ethnicity data were not collected for the medical device participant sample. We acknowledge that designers with different backgrounds and personal and social identities from the ones recruited may leverage different strategies or do so in diverse ways that were potentially not captured in this study.

3.6 Conclusion

This study investigated design practitioners' prototyping strategies to engage stakeholders during the front end of design across three design domains. Further, it described patterns of use across designers' project contexts. The findings suggest that the prototyping strategies evaluated were transferable across domains. All 17 strategies were used by at least four participants across domains. While 12 strategies were used by consumer products, automotive, and medical device industry participants, two were used by participants between the medical devices and consumer products domains, and three were used by participants between the medical devices and automotive domains.

Practitioners used strategies in consistent ways across domains, with some variations which we posit were adaptations based on different dimensions of their context, e.g., project goals, stakeholders engaged, and the situation characterizing their stakeholder interactions. The main findings are supported by general design literature describing key features of design practice, and adaptations designers make to design processes to suit the design task at hand. This paper has implications for design practice, education, and research, including the detailed description of prototyping strategies to capture the actions and distinct applications of use that can support experienced practitioners in adopting and adapting new methods, and novice

designers in the development of important design skills. Ultimately, the outcomes of using prototyping strategies to engage stakeholders during front-end design should support the development of design solutions grounded in stakeholder wants, needs, and priorities which is critical for design success.

3.7 Acknowledgment

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Chapter 4 Prototyping Strategies to Engage Stakeholders During Front-End Design: Supporting Intentional Use in Design Education[5]

Abstract

Engaging stakeholders early and throughout design processes is necessary for product success as it supports the alignment of design decisions with user and stakeholder needs and preferences. Leveraging prototypes to engage stakeholders can help designers develop common ground with stakeholders, especially during "front end" design activities, such as problem scoping and product requirements development. While design practitioners intentionally use prototypes to engage stakeholders in a variety of ways including during the earliest stages of design, research suggests that novice designers are not as intentional or comprehensive in their approaches. Therefore, we developed in-depth narratives constructed from practitioners' real design experiences to demonstrate to novice designers how design practitioners use prototypes for stakeholder engagement during the design front-end. Further, we described strategies that could be incorporated into engineering classrooms and suggested ways to support more intentional uses of prototyping strategies by students to engage stakeholders during the design front-end, including through the use of a novel prototyping planning tool.

[5] This chapter was co-authored with Shanna Daly, Grace Burleson, Marianna Coulentianos, and Kathleen Sienko, and was accepted under the title, "Using Practitioner Strategies to Support Engineering Students' Intentional Use of Prototypes for Stakeholder Engagement During Front-End Design" for a 2022 Special Issue of the *International Journal of Engineering Education.*

4.1 Introduction

Central to successful design processes is the involvement of stakeholders, including people who use, affect, or be affected by design decisions and/or outcomes. Prototypes support communication, enabling designers to explain concepts, and importantly, to obtain feedback from stakeholders [14,15]. Using prototypes to engage stakeholders, especially during the early, "front-end" stages of design, can facilitate iterative gathering and synthesis of stakeholder perspectives [7]. Prototypes can help elicit design information about stakeholders' latent knowledge and deepen designers' understanding of important needs [34,46], both of which are key aspects of effective front-end design work [11,157]. Engaging in early, exploratory prototyping during the design front-end supports designers in the development of successful design outcomes [158]. Although sources highlight the value of using prototypes in the earliest phases of design processes [13,74], prototypes are commonly emphasized during back-end engineering design stages, and framed as tools to be used once solution concepts have been selected [24,25,159,160].

During the back end of design, both novices and experienced designers have been shown to recognize weaknesses in their designs via physical prototyping [123]. However, more experienced designers employ different approaches than novices do [9,17], which have been characterized as "designerly ways" of thinking, acting, and being [161,162]. Specific to prototyping, Hilton et al. [33] showed that experienced design practitioners were purposeful about their prototyping, using intentional approaches to achieve prototype functionality during a build-test design project. Other research has also found intentional use of prototyping by experienced designers, specifically during front-end design activities involving stakeholders [130,132,146]. In addition to design experience supporting strategic uses of prototypes, Elverum

et al. [40] found that design aspects such as prior knowledge of the problem space, and the solution's level of user interaction, could influence practitioners' prototyping approaches.

Prior work has shown that engineering students may not use prototypes to their full potential. Specifically, engineering students have been found to use recommended prototyping practices unintentionally and to a limited extent, especially to support activities such as problem definition [35]. In a study comparing practitioners' and novice designers' perceptions of prototypes, novices held a relatively narrow conception of prototyping, while practitioners considered prototypes more broadly as tools for learning, communication, and decision-making, in addition to functional testing [26]. As novices tend to perceive prototypes mostly as tools for building and testing, and use largely unintentional prototyping approaches, they would benefit from tools that support the purposeful use of prototypes to engage stakeholders during front-end design activities.

Engineering education introduces prototyping in a variety of courses, particularly through experiential design courses such as capstone design [163]. Generally, engineering design textbooks emphasize prototyping as a specific stage of a design process, and as a tool for verification and validation purposes [24,25,159,160]. Engineering pedagogy that has been used in capstone design emphasizes back-end uses of prototyping, particularly in testing and implementation, through the creation of functional prototypes (i.e., "working prototype") either as physical or virtual models (e.g., [22,164,165]). Examples of prototyping educational tools include frameworks such as the *conceive-design-implement-operate* framework for mechanical engineering capstone courses, which promotes the use of prototyping during the implementation stage [166]. Other interventions have focused on the development of prototyping approaches to improve desired functional performance outcomes (e.g., Dunlap et al. [22], Camburn et al.,

[32,44]) or the consideration of ergonomics and human factors in engineering product design (e.g., Ahmed and Demirel [167,168]).

More recent developments in pedagogy to facilitate human-centered design within engineering curricula consider prototyping as a process that supports holistic design decisions. The *Prototype for X* framework, for example, guides students through three lenses of human-centered design to consider technical feasibility, business viability, and user desirability while prototyping [100]. With direction on how to use the *Prototype for X* framework, novice designers were able to improve products' technical quality, manufacturability, and user satisfaction, while also expanding their perceptions of prototyping, especially when the instruction prioritized a new perspective rather than a previously held notion of prototyping, e.g., that prototypes are primarily useful for the technical feasibility lens [101]. Another tool, the *Prototyping Canvas*, which was validated with design practitioners through design workshops, aims to support purposeful prototyping, encourages designers to determine what stakeholders will be involved in the prototyping effort and what communication strategy can be used when gathering feedback on the prototype or explaining a concept using the prototype [143]. Additionally, the *Prototyping Planner* provides four steps to support novices in prototyping more purposefully and using prototyping results when making design decisions [169]. While this tool was successful in supporting novices to prototype purposefully, Hansen et al. [169] found that it was not without challenges. For example, some students perceived the format and content of the planner to be confusing and needing more description. Overall, there is an increasing emphasis on pedagogical tools to support purposeful prototyping, including with stakeholders. However, these tools seldom provide explicit and actionable strategies to engage stakeholders with prototypes during the front end of design.

Engineering students have been reported to encounter multiple challenges when trying to engage stakeholders during front-end design work, including navigating conflicting or non-direct information from stakeholders [170] and gathering rich information about stakeholders' values and experiences [171]. Recognizing these challenges students encounter, in our work, we sought to collect evidence of strategic ways that practitioners have successfully engaged stakeholders using prototypes. Practitioners have real-world experiences during which they have likely worked with a more diverse set of stakeholders, used prototypes in a greater variety of ways, and developed more specific strategies about how to best use prototypes than student designers. Thus, investigating their experiences can contribute to how we support students in the development of their design skills. In this paper we provided in-depth examples of practitioners' uses of prototyping strategies during front-end design to engage stakeholders to expand the existing tools and techniques available to teach prototyping for stakeholder engagement in engineering curricula. We also discussed ways these situated examples could be used within engineering design education.

4.2 Methods

The aims of this paper were to 1) provide in-depth descriptions of how design practitioners have used prototyping strategies to guide their front-end design engagements with stakeholders, and 2) discuss how these contextually-rich descriptions could be used within an engineering education setting. To address the aims, our work was guided by the following research question: *How do design practitioners use prototyping strategies to engage stakeholders during the front end of design?*

To address this question, and present the findings in a way that could support students' usage of the strategies in their own work, we chose to include data from three practitioners and

share their experiences in narrative form. Narratives are descriptive and can convey the uniqueness of experiences in depth [79]. Additionally, narratives can outline a storyline and human action, facilitating communication about the event or experience to the reader [172]. These characteristics of narratives aligned with our goals to support broader recognition by students of the ways prototypes can be used during early design work to engage stakeholders and the translation of these strategies into students' own design projects.

4.2.1 Participants

Three participants, who we call Elaine, Brian, and Robin (pseudonyms), to protect their identities, were selected from an existing larger set of data collected from 36 design practitioners, including 22 participants from an earlier study [146]. We used a purposeful sampling technique to recruit these participants, seeking those with prior experience using prototypes to engage stakeholders during the front end of the design of mechanical or electromechanical products or systems. Elaine, Brian, and Robin were design practitioners from the of consumer products, automotive, and medical devices industries with 29, 4, and 12 years of design experience, respectively. One participant was a woman, and two were men. Elaine and Robin had senior roles on their design teams, while Brian was a systems team member.

The three participants were selected for this paper based on multiple factors, including the breadth of strategies used within and across the experiences they described, the variety of strategies they discussed, and the level and amount of project details they provided. Further, the chosen participants provided clear and succinct examples of the prototyping strategies they used to engage stakeholders for problem scoping, requirements development, and early concept exploration. Finally, the three selected participants clearly articulated intentionality across their prototyping approaches.

The specific strategies we chose to highlight in the narratives were informed by an informal assessment of common engineering design texts and prototyping literature, and came from a larger set of prototyping strategies for stakeholder engagement during the design front-end identified in prior work [146]. Based on this informal assessment, we opted to detail strategies that were not commonly named in engineering design texts (e.g., [24,25]), and strategies that novice designers have been shown to rarely apply during front-end activities with stakeholders [35], e.g., to promote non-superficial engagements, to support problem scoping and requirements elicitation, and to identify broader contextual factors and usability problems.

4.2.2 Data collection

We employed a semi-structured interview format, with questions focused on concrete experiences of prototype use to engage stakeholders during front-end design work. The questions helped information about specific front-end design work that the participants elected to share with us including: the phases of design work during which they engaged stakeholders with prototypes, the types of prototypes they used, the structure of their stakeholder interactions, the goals of their interactions, and if and how their prototyping approaches varied across stakeholder types and front-end design activities. The protocol was iteratively developed and piloted numerous times. One interview lasted one hour, and the two other lasted 1.5 hours. The three interviews were conducted remotely.

4.2.3 Data analysis

The narratives were constructed from the full interview transcripts, with a focus on the specific front-end design situation the participants described. We were guided by recommendations for constructing narratives discussed by Patton [79], including that narratives

should be descriptive enough to convey the uniqueness of each one. We aimed to provide adequate description while not identifying participants or details too specific about the artifacts they were designing.

To create the narratives, interview transcripts (previously analyzed for strategies used) were reviewed to identify a specific project story that could be described. We used an existing coding scheme comprising 17 front-end stakeholder engagement prototyping strategies [146] to identify relevant excerpts of strategic prototyping use with stakeholders for potential inclusion in the narrative. The "coding stripes" function of the qualitative analysis software NVivo 12 was used to examine the context above and below the coded excerpt, i.e., strategy. Subsequently, these excerpts were organized thematically by strategy in a word-processing document, where the story narrative was then developed to include participant and project background information as well as framing for each of the included excerpts.

Although the three transcripts selected included references to multiple projects and prior experiences, one project from each participant was included in the story narratives below for conciseness. Participants were provided with the opportunity to read and revise their story narratives through a member checking process.

4.3 Findings

The findings include three story narratives that describe three participants' uses of prototyping strategies to engage stakeholders within one of their front-end projects. Across the three narratives, we highlight eight of the 17 strategies identified in prior work. Each excerpt is framed using supporting text and explanation to contextualize these excerpts throughout the narratives.

4.3.1 Narrative #1: Elaine

At the time of her interview, Elaine was a human-centered design practitioner with 29 years of experience in a research and development role at a large consumer products company. Her past design experience ranged "from the upstream problem identification … to the downstream end-market." Her work in consumer goods catered to international markets, primarily with experiences in Europe and the United States.

Elaine's front-end design prior work experience included uncovering customer needs and evaluating newly developed technologies, which Elaine described as a "back and forth between what's possible and what's needed." In this narrative, we highlighted her experiences involving the use of prototypes for stakeholder engagement in one of the projects she explained.

Elaine worked on packaging innovation for a consumer product, specifically seeking ways to "elevate the role of the packaging so [it's] more useful during the product usage phase." During a front-end design phase focused on identifying product requirements that would be of value to customers, as well as understanding how customers perceived the different embodiments of those requirements, Elaine intentionally used prototypes to engage stakeholders to answer key questions about possible ways to open and close the package. Highlighted below are excerpts from her interview that demonstrate how she used prototypes to help define a sealing requirement; specifically, she used prototypes to explore customer preferences for a hermetically sealed package or a partially sealed package. She explained:

> *We had some key business questions around, "What are the best ways of doing [the new packaging], and how resealable does the package need to be?" We know that Ziploc™ is*

the standard of excellence. Consumers talk about that. But a Ziploc™ is very hard to do and expensive to do on a [specific product] pack …

… we quickly learned with consumers that whilst they like the idea of the Ziploc™, they would never actually close it in use […] it's too fiddly. There's no way you're going to do it up in between. But then I thought, I don't know if they actually need it hermetically sealed or whether they just need to have the emotional reassurance that it's protecting the product. [The questions were] how far do you need to go because the more "hermetic" you make the seal, the more expensive it's going to be and the more complicated it's going to be to manufacture. So what do we actually need and what are the requirements for a closing package.

Elaine described the questions her team had related to developing this specific requirement: What is needed? What are the requirements for a closing package? To what extent does it need to seal? Does it need to be hermetically sealed? Every variation of this question required input from stakeholders. To answer these questions, Elaine's team first developed a collection of prototypes focused on resealing that were stripped of unnecessary complexity or irrelevant details:

We prototyped that up pretty quickly. You can cut a Ziploc™ bag apart. You can cut up a [product] bag with a pair of scissors and you can glue it in there. We created a bunch of prototypes that were real simple. They were focused on the reclosing. They weren't printed. They had no [branding] on them because that would have been an extra level of

complexity to work that out and that wasn't important. And the […] brand, it wasn't important at that point either.

Then, Elaine's team strategically used these prototypes for stakeholder engagement to support their goal of determining the requirements for closing an innovative package. In the excerpt above, Elaine applied the strategy *"Show the stakeholder multiple prototypes concurrently."* She described how the use of multiple prototypes at the same time helped her team define the product requirement. By making multiple prototypes that varied in terms of the extent to which they sealed, along with multiple embodiments of prototypes that were similar in terms of their ability to seal, Elaine was able to elicit consumers' true needs through a planned sorting activity:

[Do] people need a pack that seals fully? So let's do a range of different degrees of sealing. Let's do multiple executions of how you could do that sealing to understand what degree of sealing do we need. ... I typically get [consumers] to do a lot of sorting exercises and ranking exercises without a lot of discussion because what I'm doing is behavioral observation… I have designed a series of stimuli that I know that they increase in the level of sealing and then there's some different executions of the ways to seal. And then I'll ask them to do sorting. I'll ask them to do ranking and I will then say ah, interesting. All the ones that sealed fully landed in the middle. And the ones that seal partially were actually put in the same group. They were fine.

The mistake I see a lot of people making is that they try and just do one execution of an idea and then [stakeholders] get hung up on the execution rather than the specific idea, and so you need a range of different executions in an idea so you can understand the idea, not the execution… Consumers can get really hung up on a tiny little detail like "That's red and I'd never have something red in my house." And you're thinking oh, red wasn't the important thing. And then you can end up going down this rabbit hole where you don't know if she was interested in that benefit or not but she got so hung up on the fact that it was red.

That's why I think you need to have a range of different ways of doing it. If your hypothesis is, it needs to be partially sealed, what are different ways that I can do the partial sealing? And then if [the partially-sealed prototypes] pretty much all rise to the top then I know that that's of interest. Maybe there's one that isn't and I think, 'I see why. It's because we forgot to put the handle on that bag'"

Further, Elaine mentioned that when she uses the strategy "*Show the stakeholder multiple prototypes concurrently,"* she often aligns the resolution of the prototypes, defined as the strategy "*Standardize the refinement of the prototypes shown to the stakeholder:"*

You can't take a whole lot of mocked up prototypes and throw a current market product in the middle of them. It's clear what's going to win because of the level of resolution. So they all lead to that same resolution.

Elaine emphasized that the "right" resolution is determined by the posed design question. Also evident in Elaine's discussion of her use of the strategy "*Show the stakeholder multiple prototypes concurrently"* were two other intentional front-end design prototyping stakeholder engagement strategies. She used the strategy *"Prompt the stakeholder to select prototypes and prototype features"* by asking participants to rank the ideas represented by the multiple prototypes shown *("I have designed a series of stimuli that I know that they increase in the level of sealing and then there's some different executions of the ways to seal. And then I'll ask them to do sorting.").* And, she noted that during the engagement session, she used the strategy *"Observe the stakeholder interacting with the prototype(s),"* as she observed stakeholders' behaviors as they examined the different seals across the prototypes.

4.3.2 Narrative #2: Brian

At the time of his interview, Brian was a mechanical engineer with an advanced degree in design engineering and four years of design experience working for a large automotive company. In his role as an automotive engineer, he used customer research to generate new concept solutions, thus mapping customer wants and needs to potential new vehicular features and functions. His role aligned with front-end design work, which entails problem scoping and definition, requirements development, early concept generation and screening, among other activities.

In one of his projects, Brian was tasked with exploring potential improved means of entering and exiting vehicles:

> *[We looked] at the entry experience and the exit experience of getting into a vehicle and out of a vehicle and how we can leverage technologies to simplify that experience, so*

reducing the amount of interactions that are needed, the amount of physical buttons and trying to rethink, from a blank slate perspective and not really be anchored by legacy aspects of automotive design related to internal combustion engines or related to fully manual driving and things like that. Trying to really rethink, from a blank slate, how could we simplify the experience of getting into a vehicle and starting to use the vehicle and exiting the vehicle.

Brian's explanation of the project emphasized his team's "blank slate" perspective—they aimed to explore a broader solution space that was not constrained by historical and current practices in vehicle design. In his work, he described the value of using prototypes to explore ideas. For example, when prototyping internally with other teams in his company, his team used a variety of prototype types, such as sketches to convey different potential component configurations for the vehicle:

A lot of it started with sketches between myself and another engineer that was working on the project. A lot of the very, very early prototypes were kind of us sitting down and scratching down on some pieces of paper different ways of laying out different controls and ways of combining and optimizing controls for the vehicle.

During Brian's concept exploration process he interacted with a variety of stakeholders including consumers as well as sub-system engineering groups within his company. When it came to preparing for the stakeholder engagement, Brian carefully considered who he was engaging before developing prototypes and plans for the engagement. Understanding specific stakeholder groups within the company was important to facilitate communication of information via the prototypes and to avoid negative outcomes due to cultural norms specific to

the stakeholder groups. He explained that in a large company like his, there needs to be careful consideration of prototyping approaches when communicating between groups, which sometimes includes limiting the amount of information provided with a prototype:

> *The biggest thing for engaging with other groups in the company, it's mostly political, really. We want to provide for certain discussions, like the bare minimum amount of information possible to prevent confusion or to prevent people from jumping to conclusions about the design [...] So you have this core group that wants to make everything the same, and then you have [another group] who wants their product to be unique, so you kind of have these butting of heads […] A lot of it is trying not to step on each other's feet and trying to show that you understand the values of other groups, even if they're not in the best interests of whatever your discipline is.*

Brian emphasized that the type of prototype in combination with carefully planned additional information to be shared during the engagement could help shape the discussion and when needed, narrow the focus of the engagement to support specific information elicitation or conveyance goals. When he and his team wanted feedback on overall ideas, they brought "generic" prototypes:

> *In certain situations, we make something extremely generic. The most generic way possible to kind of describe the idea … we would basically just try to take the form away from it as much as possible. So if you had four buttons, instead of having some kind of covering that goes over it, we would just show it as four separate buttons […] we were trying to, like I said, not step on people's toes, but also kind of demonstrate the merit of*

the design from [this particular stakeholder group's] perspective as far of being able to be packaged in a lot of different forms.

The approach Brian described aligned with the front-end design stakeholder engagement prototyping strategy *"Lessen a prototype's refinement when showing it to the stakeholder."* In the scenario described above, Brian purposely opted to create a not-too-specific version of their idea to be able to socialize his team's concepts with another sub-group and do so in a way that conveyed they were open to the stakeholders' input.

On the other hand, when Brian aimed to elicit feedback from engineers and stakeholders from other groups in the company regarding new potential technologies, he used the strategy "*Polish the prototype(s) shown to the stakeholder"* to convey how new components would be compatible with previous products and hardware, and that it was not a start-from-scratch scenario:

Then in other situations, ... a big issue we've been running into is trying to use carryover hardware from previous products, so if we're discussing it with certain teams, we'll dress it up and show how it could be easily integrated into older pieces of hardware to kind of illustrate the point that this isn't something that's going to be a completely brand-new starting point.

Brian used the same strategy when preparing prototypes (here, virtual renders) to communicate with management stakeholder groups:

So sketches were a big thing for working quickly amongst people like in my own group that were more familiar with the concepts. Then we had more kind of dressed up renders

for showing other groups and management… [For those groups], usually it would be more of higher fidelity [virtual] renders. So aesthetic was really important and the actual functionality [of the prototype] was not very critical because that was something that was kind of laid out in the rest of the presentation.

When seeking answers to specific design questions about the feel or experience of a concept, Brian used physical prototypes so that customers could interact with them:

It entirely depends on the audience [...] With customers or users, it's really important that they have something physical to kind of have a real interaction with of some kind. We weren't so concerned about the fidelity [or] the aesthetics, but mostly … looking at if you have a toggle switch or something like that that is spring loaded, you want to have something [similar] in your prototype to kind of give somebody a sense of what kind of interaction they would be experiencing. … You don't want just a picture of something and have some questions about, 'well does it stick to the one side or does it spring back?'

He mentioned that he used the strategy *"Encourage the stakeholder to envision use cases while interacting with the prototype(s)"* when a prototype could not physically support a particular desired interaction or convey specific information:

There's been situations where we've been trying to demonstrate designs that don't work where we had a picture of it and we really have to walk people through. 'Imagine rotating the [component] back and forth' and trying to get them to envision a physical interaction. It works to some degree, but having a physical prototype can really cut through some of that. It's just really a balancing act of how much time and resources you

want to put into that, versus just being willing to spend more time with people to explain the situation.

Brian also discussed using the "*Show the stakeholder multiple prototypes concurrently*" strategy when obtaining customer feedback:

…if we're showing somebody the spectrum [of prototypes], the one end of the spectrum is basically production vehicles, what's being sold today, and then if you compare that to a rudimentary prototype, that's not really a fair comparison. You have different visual cues, different tactile feedback, one just looks like a cheap science project and the other one is very refined, so a big thing for that was making sure that we were putting all of them on the same level of fidelity.

Brian emphasized that standardized fidelity among prototypes was important when showing multiple prototypes to customers ("*Standardize the refinement of prototypes shown concurrently to the stakeholder*" strategy). For example, maintaining a consistent fidelity among the prototypes was especially important when he asked stakeholders to compare a new proposed design direction with the previous (market available) design.

4.3.3 Narrative #3: Robin

At the time of his interview, Robin was a senior program manager with 12 years of design experience working in customer-centric innovation projects at a large medical device company. The project Robin described included front-end design work for an electro-mechanical device with a specific application in a catheterization laboratory. The project focused on a product the company had sold in the past, but was off the market at the time. As the company

was interested in re-introducing a similar product to the market, Robin's team was engaged in front-end work to both understand potential interest in the product area and to develop product requirements.

Since the product had already been on the market, Robin's team had some prior knowledge about the product category. However, the design team was exploring a wide variety of layouts—how prior and new features were arranged—that could add new value to customers in a future product. The team understood they needed for example, functions to control speed, attach or detach part of the catheter, and control articulation of the end of the device.

While scoping the problem, the team wanted to determine end-users' preferences for requirements such as convenience, safety, and control during medical procedures. To address the questions about requirements and functions, Robin engaged stakeholders using multiple prototypes:

> *In that case, we prototyped a wide variety of shapes and configurations. We did some industrial design work that was mostly sketches, and 3D CAD, and then from there we decided to 3D print different embodiments. In the end, I think we threw seven different concepts at [stakeholders and end-users] that were all radically different, including a modular type design where they could then build their ideal layout of the system."*

In the previous excerpt, Robin described the use of multiple prototypes to engage stakeholders, defined as the strategy "*Show the stakeholder multiple prototypes concurrently*." Robin described how the prototypes represented radically different concepts and how the team

included a modular design that would enable stakeholders to assemble their version of an ideal layout.

To elicit priority information, Robin probed stakeholders' preferences by posing open-ended questions about likes and dislikes for each prototype, and by enabling stakeholders to physically show the team arrangements of parts that mapped to their conceptions of certain requirements such as ease of use:

> *Instead of saying 'Which one out of these seven do you like, and what do you like or not like about them?' ... we did that, but then we also said 'Okay, here's a pile of 3D printed parts, with bits and pieces of the other ones. How would you arrange them in a way that would be easiest, or most logical, or straight forward, or intuitive to use?'*

With the modular prototype, the design team leveraged the strategy *"Task the stakeholder with creating or changing the prototype(s)"* to contribute to their understanding of stakeholders' needs, wants, and priorities. Additionally, the strategy allowed the team to investigate how the different arrangements of features in the prototype aligned with requirements.

Robin explained how it would not have been ideal to evaluate other design requirements such as convenience, feelings of safety, and control, in isolation, but that they had to be evaluated in the context of the task the features would support:

> *You really don't want to evaluate features by themselves. They call that feature silos. It would be like saying 'What color do you like best?' Well, what color for what? or 'Which*

one of these knobs feels best?' Well, really it depends on where the knob is located... Are [they] trying to use it for leverage, or does it get in the way? … We recognize the risk of [evaluating features by themselves], but that was the value in having them put it all together, and then to be able to move things around.

At the end of the day, it was really a generic shape of the handle body, if we want to start there. Instead of picking a more radical shape, it was…think of it as just a submarine shape. A lot of catheter handles look the same, to be honest, so [we started] with a really basic elongated shape and provided different concepts for a slide actuator, a rotation knob, a locking feature, a [specific device function] ... The idea was that you could have your industrial design feed the different shapes of some of those [handle shapes], but we decided that for the "build-a-handle" exercise, it was more about relative location, and access to the features, than it was picking things based on aesthetic, or tactile feedback.

In describing his use of the strategy defined as, "*Task the stakeholder with creating or changing the prototype(s),*" Robin pointed out how the engagement went beyond stakeholders arranging prototypes in a way that was aesthetically desirable to them. Instead, the design team used mock procedures to enable stakeholders to more holistically evaluate their self-assembled prototypes' abilities to achieve the intended task:

It was really like given all these required parts, how could they get everything onto the catheter handle. We gave them modeling clay to stick on the features just stick them where it's desired, and then had them go through the activity of holding it in their hand,

or laying it on the table, and using it. Just like the end user, seeing what made sense. Seeing if the way that they put it together was appealing or not. There were a lot of cases where they started out by arranging things in a way that was aesthetically pleasing, but after going through the mock procedure they realized that things were in the wrong location. That it looked nice, but there was no way that you could get to something. Or features just kind of got in the way and it was cumbersome. Which is really what we were after.

This example emphasized the importance of evaluating a prototype, or more broadly, a concept solution in its context of use through the strategy *"Encourage the stakeholder to envision use cases with the prototype."* In summary, Robin first encouraged stakeholders to participate in the creation of prototypes to communicate their wants and needs to the design team. Second, Robin invited stakeholders to simulate use cases to better understand design constraints that might not have been apparent from appraising the aesthetically-driven prototypes alone. Furthermore, the envisioning task provided feedback about how the device performed during use that complemented the feedback about the stakeholders' preferences.

4.4 Discussion

Our findings provided in-depth examples of practitioners' uses of front-end prototyping strategies to engage stakeholders. The three narratives highlighted various strategies and contextualized their use to provide a deeper understanding of how practitioners used them intentionally. Elaine's narrative highlighted the intentional use of prototypes with stakeholders as she designed engagements that aligned with the design question or goal at hand. For example, she observed participants as she tasked them to sort prototypes, while using multiple prototypes.

As a result, Elaine was able to gather relevant information that corresponded to her team's design questions. Brian's narrative also highlighted his intentionality in designing prototypes that aligned with his design goals as well as stakeholders' expectations. For example, he employed strategies that prioritized prototype refinement. By considering both the type of feedback that he and his team needed as well as stakeholders' perspectives, he was able to focus engagement on his particular design goals, manage expectations, and collect relevant information. Lastly, Robin's narrative demonstrated the intentional use of prototypes to support the development of requirements and to understand how potential concepts would perform by having stakeholders use prototypes in simulated use settings. For example, Robin asked the stakeholders to create prototypes during the engagement session to understand potential interactions users could have with desired features; he also asked stakeholders to use prototypes in a simulation to gather feedback on use behaviors.

4.4.1 Implications

The narratives themselves provide a way to support engineering designers in broadening their understanding of how prototypes can be used in a design process. They also demonstrate the carefully planned use of prototypes prior to engaging stakeholders—the practitioners highlighted in these narratives had specific questions that they wanted to answer and therefore made specific decisions about what types of prototypes should be used with what types of stakeholders, and how they should engage with stakeholders. The narratives demonstrated strategies that can be applied throughout front-end design work, consistent with a recognition, including in examples of industrial processes [14,29], that prototyping is not a discrete design stage, but an ongoing design activity. In Table 9, the strategies from the narratives are categorized into three groups: prototype interactions, prototype refinement, and prototype

comparisons to facilitate discussion and subsequent use. Although there are other possible ways to categorize these strategies, this specific categorization allows for distinguishing strategies to apply during an engagement from other strategies necessary to prepare (i.e., build and select prototypes) for the engagement.

Table 9 Stakeholder engagement strategies presented in the story narratives.

Strategy category	Strategy	Description	Narratives
Prototype interactions	*Observe the stakeholder interacting with the prototype(s)*	Prompt the stakeholder to interact with prototypes while observing the interaction.	Elaine
	Encourage the stakeholder to envision use cases while interacting with the prototype(s)	Prompt the stakeholder to imagine how they would use the prototype in various use cases.	Brian, Robin
	Task the stakeholder with creating or changing the prototype(s)	Prompt the stakeholder to create or modify the prototype(s) by physically altering prototypes, writing, or drawing ideas.	Robin
	Prompt the stakeholder to select prototypes and prototype features	Ask the stakeholder to choose or prioritize ideas based on provided prototypes.	Elaine
Prototype refinement	*Standardize the refinement of prototypes shown concurrently to the stakeholder*	Present prototypes that are at the same level of refinement (fidelity, functionality, and finish) when shown simultaneously to the stakeholder.	Elaine, Brian
	Lessen a prototype's refinement when showing it to the stakeholder	Engage the stakeholder with less sophisticated and/or incomplete prototype(s) compared to the current project status.	Brian
	Polish the prototype(s) shown to the stakeholder	Create or modify a prototype to show to the stakeholder that more closely resembles the final form of the concept versus the current status of the project.	Brian
Prototype comparisons	*Show the stakeholder multiple prototypes concurrently*	Prompt the stakeholder to compare options using multiple prototypes of different needs, concepts, features, form factors, requirements, or engineering specifications.	Elaine, Brian, Robin

Within the "prototype interactions" category, strategies focus on stakeholder engagement activities such as observing stakeholders interacting with the prototype and tasking the stakeholder to change the prototype. Instructors may encourage the use of strategies in the

"prototype interactions" category when asking students to solicit information, particularly from end-users, during problem scoping and requirements development stages. Strategies within the "prototype refinement" category correspond to the prototype's appearance or level of detail for the purpose of stakeholder engagement, such as lessening, polishing, or standardizing the prototype's refinement. Within engineering design courses, the introduction of "prototype refinement" strategies may be best suited when instructors are offering guidance on prototype fabrication, e.g., what type(s) of prototype(s) should be made and how refined should it/they be? While the development of prototypes should involve conversations with students about traditional prototyping aspects such as materials selection, fabrication, etc., instructors could also use this opportunity to probe students about the goals of their planned stakeholder engagement(s) and the type(s) of stakeholder(s) to be engaged to ensure that the level of refinement of the prototype(s) to be created will support their engagement and information gathering goals. Within the "prototype comparisons" category, using multiple prototypes enabled engineering designers to prompt stakeholders to compare across alternatives. Instructors can encourage students to bring multiple prototypes to stakeholder engagements during front-end design stages, when their goals are to elicit broad feedback across a variety of topics, convey to stakeholders that various design alternatives are being explored, and invite genuine stakeholder perspectives, consistent with what has been found about medical device design practitioners' use of multiple prototypes [132].

In the following sections, we provide additional recommendations for engineering educators to support the use of these practitioner strategies in their courses as well as compare our findings with existing literature.

Add a focus for prototyping on the front end.

Engineering design pedagogy for prototypes often focuses on prototyping methods for functionality, particularly during back-end design stages, such as concept selection, verification, and validation [163,165]. However, our findings revealed and contextualized ways in which prototypes can be employed during front-end design stages to identify design directions, develop requirements and specifications, and guide early concept development. Early-stage and low-fidelity prototyping has been found to improve problem reframing and the creative ability of designers [84], and facilitate discussion with stakeholders about high-level ideas [34]. Thus, we recommend that engineering design educators encourage students to consider how prototypes can support their design work early in their processes, including as tools for problem definition, requirements development and translation to engineering specifications, concept exploration, and stakeholder engagement broadly. While prior work in engineering design has focused on using prototyping to consider aesthetics, ergonomics, user satisfaction, and other desirability considerations (e.g., [100,168]), we propose that a broader elicitation of information from stakeholders can be accomplished through the use of strategic prototyping methods, e.g., defining specific requirements, as described in Elaine's and Robin's narratives.

Build engineering students' repertoire of strategies to engage stakeholders using prototypes.

Engineering design practitioners leverage a collection of strategies to engage stakeholders during front-end design stages [146]; eight of these strategies are discussed in the three narratives in this paper. Building novice engineering designers' repertoire of strategies may support their recognition that there are many ways to use prototypes. Novice engineering designers can only intentionally apply what they know. Research has shown, for example, that novice designers' prototyping decisions pertaining to fabrication were driven by the methods with which they were

most familiar [19]. Building students' repertoire of prototyping strategies can also support their approaches to engaging with stakeholders, as it has been shown that students can sometimes struggle to delve into some stakeholders' experiences and encourage deep thinking [171].

Engineering educators can share the strategies summarized in Table 9 and incentivize their use by asking students to outline and justify prototyping and stakeholder engagement decisions as they would justify other design decisions. Further, instructors can diversify graded assignments in their design coursework and include assignments that motivate students to select a range of prototyping strategies for engagement with stakeholders, particularly to define problems, develop requirements, translate requirements into engineering specifications, generate concepts, and select concepts while taking stakeholders' perspectives into account. In addition to the strategies in the summary table, the three narratives can be used to prompt students to analyze, reflect, and analogize ways that the use of strategies can contribute to their own design projects.

Plan a specific question to answer with prototypes through stakeholder engagement.

The three narratives presented in this study demonstrated practitioners' deliberate use of prototypes to engage stakeholders during the front end of design. Each strategy was used purposefully to achieve a named goal in the context of these practitioners' projects. Thus, we recommend that engineering students, prior to engaging stakeholders, determine *what they need to know in order to move forward,* and from there determine: *1) which stakeholder or stakeholder type is best suited to provide that knowledge, 2) which prototypes will support accessing that knowledge,* and then *3) what strategy or strategies to use.* We depict this iterative and interconnected process in the tool we developed, called the Prototyping Tool for Front-End Stakeholder Engagement [173], and show this tool in Figure 1.

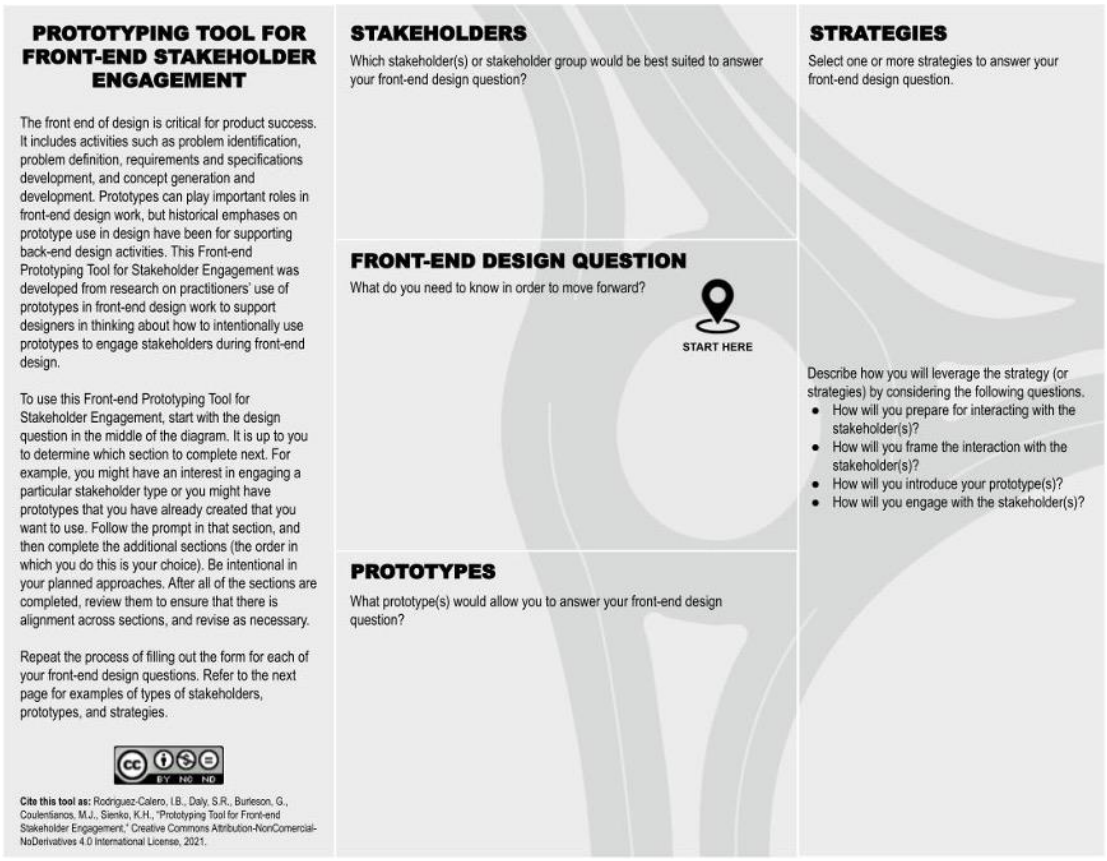

Figure 1 Considerations for stakeholder engagement using prototypes during front-end design as presented in [173].

The order of the prompts described in the tool may vary by project. To acknowledge this variation, we overlaid the questions on top of a representation of a traffic circle, thereby emphasizing the potential multiple points of entry and exit. As with many other design activities, we recommend that designers employ an iterative process when determining which prototypes to use with whom and how to use them to ensure alignment with their goals.

4.4.2 Limitations

While this research outlines rich descriptions of participants' prototyping strategies, our data do not allow us to connect participants' methods to specific design outcomes or make claims about their ultimate design success. Furthermore, the narratives explored the use of prototyping strategies for front-end design stakeholder engagement in a limited set of contexts. It

is possible that the strategies are not fully applicable to particular design contexts. It is also possible that the strategies could support front-end stakeholder engagement with a broader set of stakeholders, during additional design stages, and within different scenarios of use.

4.5 Conclusion

Our findings highlighted several ways design practitioners use prototypes with stakeholders during front-end design activities. By presenting the strategies in a narrative format, we showcased important contextual details and rich examples, e.g., designer goals, stakeholder priorities. The narratives offered an opportunity to highlight in-depth examples of intentional strategy use across three different design projects. We recommend that early-career designers learn from the experiences presented in the narratives to inform their own approaches and strategies. To facilitate that process, this paper introduced a tool to support designers in their planning. Ultimately, we recommend more inclusion of prototyping during front-end design stages, especially to engage stakeholders.

4.6 Acknowledgements

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Chapter 5 Discussion: Contributions, Implications, and Future Work

5.1 Chapter summaries

5.1.1 Prototyping strategies to engage stakeholders during front-end design: Design practitioners' approaches in the medical device industry

In Chapter Two, I presented a study that aimed to describe prototyping strategies design practitioners intentionally used to engage stakeholders during front-end design. The following research question guided the study: What prototyping strategies do design practitioners use to engage stakeholders in the front end of design? Sampling participants from the medical device field as an initial focus of investigation supported the collection of a rich data set to establish a comprehensive documentation of strategies for individual stakeholder engagements that covered a wide variety of settings including multinational companies, small startups, consulting firms, and global health organizations working on the design and development of devices across a wide variety of clinical needs and contexts of use. This study's sample consisted of 22 design practitioners who averaged over 10 years of experience (11.9 ± 9.3 years). Participants were interviewed about project experiences in which they specifically used prototypes to engage stakeholders during activities such as needs finding, requirements and specifications development, concept generation, concept selection, and concept development. Using an inductive approach, codes and definitions were iteratively developed to characterize the specific actions found in the interview transcripts.

The study presented in Chapter Two introduced 17 prototyping strategies design practitioners used to engage stakeholders during front-end design tasks. Every strategy was written so that it was descriptive by itself, while definitions and participant excerpts accompanied each strategy code. The most and least frequently described strategies were further expanded with respect to the excerpts that made up each qualitative code. Additionally, contrasting strategies to some of the most and least frequently described were further developed to illustrate the wide variety of methods practitioners leveraged in their projects.

The most frequently described strategies were (1) *Show the stakeholder multiple prototypes, (2) Brief the stakeholder about the project and prototypes shown,* and (3) *Observe the stakeholder interacting with the prototypes.* The least frequently described strategies consisted of (4) *Modify the prototype in real time while interacting with the stakeholder,* (5) *Make prototype extremes to show the stakeholder,* and (6) *Lessen the prototype's refinement when showing it to a stakeholder.* Diverse strategies further characterized from the 17 strategies uncovered were *(7) Polish the prototype(s) shown to the stakeholder, (8) Task the stakeholder with creating or changing prototypes,* and *(9) Introduce the prototype(s) to the stakeholder in the use environment.* Delving into these specific nine strategies further elucidated how design practitioners discussed stakeholder engagements with prototypes and how their active and intentional uses of strategies fulfilled diverse purposes and practitioners' goals.

5.1.2 Prototyping strategies to engage stakeholders during front-end design: A study across three design domains

In Chapter Three, I described a subsequent study to the initial context of investigation of medical device design practitioners' prototyping strategies to engage stakeholders during front-end design. The study on Chapter Three explored the transferability of 17 strategies described in

Chapter Two to other design domains guided by the same research question: What prototyping strategies do design practitioners use to engage stakeholders during front-end design? The participant sample comprised 26 participants: seven worked in the consumer products domain, seven worked in the automotive domain, and 12 were medical device participants from multinationals and startups included from the prior study for comparative purposes. This study followed a deductive approach first with the 17 strategies as a codebook, while also reading transcripts in-depth for the emergence of any new strategies in the new sample. Further, each coded strategy excerpt was further analyzed by summarizing the direct quote with respect to information about the setting, stakeholders, project goals, rationales or any other unique trait of the situation that characterized details about the strategy use.

The findings in Chapter Three showed that 12 prototyping strategies to engage stakeholders during front-end design were evident across participants' projects in the domains of medical devices, consumer products and automotive. Additionally, two strategies were found between consumer products and medical device participants, and three were found between automotive and medical device participants. While some strategies were used to a greater extent in some domain, exploring the strategies' use scenarios showed that practitioners' use of strategies was generally consistent across domains, with some adaptations, (e.g., for *brief, simulate,* and *support*), and exceptions (e.g., for *co-select*). There were additional participant excerpts coded as a strategic use of prototypes with stakeholders, particularly among consumer products domain participants, even when their actions did not precisely match the predefined strategies.

5.1.3 Prototyping Strategies to Engage Stakeholders During Front-End Design: Supporting Intentional Use in Design Education

Chapter Four involved a study that aimed to provide in-depth descriptions of how particular design practitioners used prototyping strategies in front-end design stakeholder engagements, guided by the research question: *How do design practitioners use prototyping strategies to engage stakeholders during the front-end of design?* A second aim of the study was translating the use of strategies to support their adoption in a pedagogical context. Based on this two-fold aim, I used the in-depth descriptions to create a front-end prototyping tool for stakeholder engagement, to facilitate engineering instruction and adoption of these practices in the engineering classroom. I selected three participants from the broader dataset of participants (described in Chapter Two and Chapter Three) who demonstrably applied a breadth of different strategies within their own projects and across their experiences, as well as provided clear and succinct examples from their interviews. Based on their coded interview transcripts, I constructed three narratives that followed these practitioners' front-end design projects through the lens of their use of strategies.

The findings in Chapter Four depicted the backgrounds, distinct project qualities, and specific use of strategies of three design practitioners working in three industries. The first narrative introduced the work of Elaine (pseudonyms were used to protect participants' identities), a design practitioner with 29 years of experience working in packaging innovation for a consumer product. The second narrative described the work of Brian, a design practitioner with 4 years of design experience working in automotive, particularly in the experience of interacting with a vehicle. The third narrative portrayed the work of Robin, a design practitioner with 12 years of design experience working in customer-centric innovation within the scope of electro-mechanical medical devices. Each narrative contextualized their use of strategies, while collectively, in the highlighted projects they used eight strategies out of the 17 strategies

described in Chapter Two. In the end, the practitioner narratives were synthesized into a Prototyping Tool for Front-End Stakeholder Engagement [173] that designers can use by following the prompts, which begin with a design question, and can be filled out iteratively.

5.2 Positionality

My positionality as a Puerto Rican woman in engineering and design science has both afforded me privileges and shaped experiences of marginalization that informed my epistemic frame and influenced the research process of my dissertation studies. My graduate field of Design Science, which is positioned as an engineering-adjacent field, as well as my mechanical engineering undergraduate training, inherently contextualized my work in a value system grounded in rigor, impartiality, and systematicity over lived experience. However, over the course of my interdisciplinary doctoral coursework and training, I distanced myself from positivism and rationality, as I believe knowledge is situated and co-constructed. Thus, my research design, instrument development, data collection and analysis processes reflected this shift, while not without tensions. For example, my methodological training was heavily influenced by grounded theory, social constructionism and constructivism. However, I used methods that were not necessarily aligned with those theoretical approaches (e.g., inter-coder reliability and agreement measures), used as markers of "rigor" in heavily quantitative spaces.

My background and experiences as a mechanical engineer, which included working in research and development, likely positioned me as an insider to some of my participants' groups. This positioning helped me build rapport and gave me shared language and common ground with my participants during data collection. However, I have not been in a position to make any influential design decision in an industry context, which made me an outsider to those experiences. To that end, my standing as a doctoral researcher and trainee likely encouraged

participants to share their work, potentially assuming the role of a teacher or mentor to me. My professional identities at times felt in tension with being a Latina woman. I was only aware of two design practitioners who shared my gender and cultural background, which encouraged me to be intentional about recruiting across different dimensions of diversity even with the highly specific study recruitment criteria we had with respect to the types of projects we sought to have represented. There were gaps as to who was represented in my participant samples, at first because as a research team we did not collect data on racial and ethnic backgrounds, and later, likely because of combination of factors including our outreach approaches and also existing system-level failures impacting who pursues, obtains, and remains in engineering design positions in industry.

The societal outcomes and broader impacts of my research have felt more important than broadly contributing to the body of literature in my field, which comes from a place of experiencing and witnessing exclusion in decision-making (at a systems and individual level) and the sense of urgency I place in increasing broad and equitable stakeholder participation in design processes and design decision-making. That personal stance influenced the choice for an engineering education and instruction-focused study in my dissertation. Further, I situate parts of my work in two different ways. First, I see design research and practice as meaningful mechanisms to enact change. Second, I see the prototyping strategies that are at the core of this dissertation as supporting design work being truly grounded in knowing and prioritizing a broad range of human experiences and needs.

5.3 Discussion

The studies presented in this dissertation collectively show the how design practitioners intentionally approach prototyping to engage stakeholders during front-end design activities of

tangible products, including needs finding, problem definition, design requirements elicitation, engineering specifications development, concept generation, concept selection, and concept development. The findings include a collection of prototyping strategies to engage stakeholders, the excerpts, and the exemplary quotes that defined them (Chapter 2), an investigation of the breadth of these strategies' applicability across domains (Chapter 3), and an analysis of the use of prototyping strategies to engage stakeholders in-depth within the context of three specific design projects (Chapter 4) to inform their application in design practice and education.

The following sections describe three overarching themes that draw from findings across the three studies that constitute this dissertation. The first theme consists of the findings related to the strategic use of multiple prototypes to engage stakeholders during the front end of design and the potential of the strategy to facilitate other strategic uses of prototypes. The second theme consists of a subset of strategies that were used across studies to manage stakeholder expectations. The concluding theme captures the important role the prototyping strategies that are centered in this work in the intentional engagement with end-users as stakeholders.

5.3.1 Exploring problems and solutions through multiple prototypes

In Chapter 2 and Chapter 3, the most prevalent strategy was, "*Show the stakeholder multiple prototypes concurrently."* In Chapter 4, this strategy was the only one that the three participants discussed across the scopes of the three experiences highlighted in the narratives covering three different project goals addressing different questions, in three distinct domains. Besides exploration being a key characteristic of the front end of design, the three studies highlighted active and intentional ways to embed multiple prototypes when engaging with stakeholders during front-end design activities. Chapter 4 further demonstrated the suitability of using multiple prototypes with stakeholders during design requirements elicitation and

engineering specifications development. As an example, the practitioner in the first narrative made multiple prototypes representing different form factors for a package (i.e., corresponding to reusability and reclosing requirements), and the different degrees of sealing for this package (i.e., corresponding to the engineering specification), as did the practitioner in the last narrative when engaging users about a device to be used in a clinical setting.

Design practitioners' rationales for using multiple prototypes with stakeholders can shed light into what they perceived this strategy could afford them: enabling stakeholders in making comparisons between prototypes, conveying the exploration of multiple alternatives, eliciting broad feedback from stakeholders across multiple topics, and making it easy for stakeholders to share from their perspectives (i.e., lowering the bar for critique) [132]. While the rationale for the strategy elucidates on what it afforded practitioners, multiple other strategies in addition to "*Show the stakeholder multiple prototypes concurrently*" came into play while engaging stakeholders, as the narratives in Chapter 4 illustrated. The combination of various strategies was not unusual throughout excerpts analyzed for Chapter 2 and Chapter 3, and more deeply explored in Chapter 4, suggesting that a wider array of possible outcomes from engaging stakeholders might be realized through the combination of strategies based on questions and circumstance.

In Chapter 4, the first narrative highlighted how the strategy "*Show the stakeholder multiple prototypes concurrently"* enabled the practitioner to use *"Prompt the stakeholder to select prototypes and prototype features"* and interpret stakeholder preferences across engagements which in turn was facilitated by using *"Observe the stakeholder interacting with the prototype(s)."* Further, intentionally leveraging multiple prototypes provided the practitioner in the third narrative with the ability to understand the potential layout of various features

impacting the user task by asking open-ended questions about each prototype and using the strategies *"Task the stakeholder with creating or changing the prototype(s)"* and *"Encourage the stakeholder to envision use cases with the prototype"* with the generated prototypes.

When placed in the context of a project, the use of "*Show the stakeholder multiple prototypes concurrently*" seems to suggest practitioners having multilayered and complex approaches to intentionally engaging stakeholders using several strategies within an engagement. The specific strategies which multiple prototypes facilitated can be meaningful mechanisms to exploring diverse stakeholder perspectives through methods requiring different levels of input and ownership, not just from internal decision-makers, but end-users as well. Importantly, this broadly applicable strategy illustrated that design practitioners sought stakeholder feedback, e.g., users and others external to the design team, on multiple points of potential exploration, thus being able to investigate potential requirements, specifications, concepts, and features. So even when aspects of a design might be fixed or difficult to change, it is possible to leverage divergent techniques.

Further, in Chapter 2 and Chapter 3 the intentional use of "*Show the stakeholder multiple prototypes concurrently*" and "*Show a single prototype to the stakeholder*" were not mutually exclusive over the course of a full transcript (unit of analysis). Within the scope of a project or various front-end projects, there were circumstances which warranted both. Research on using prototypes for exploration in engineering design remains limited in comparison to literature exploring iterative refinement of prototypes to achieve a final integrated design solution [30], but some work can help explain the duality found in study participants' experiences. Prior research has explored the role of sharing multiple prototypes with a peer in exploring new possible features in a design solution [134]. When a "scapegoat" idea is included in a mix of prototypes

shown to stakeholders, these have the quality of eliciting critique across ideas [174], which can be valuable information early on. With respect to users, one study investigated the influence of timing of user feedback in the outcomes of early-stage prototyping and found that underperforming teams characteristically sought feedback from users while selecting a design concept among alternatives, but did not close that loop with seeking feedback on the final concept selected [158]. The use of one or multiple prototypes with stakeholders can improve their perceived ability to comment on design ideas, but with multiple they can speak to their own experience through comparison [175]. Here, intentionality might be the key to when to leverage either approach.

In contrast to using multiple prototypes, many instances of practitioners using a single prototype with stakeholders were examined and regarded unintentional, thus they did not contribute to the counts in the analyses for both Chapter 2 and Chapter 3. For instance, placing a prototype on the conference table during a meeting was not considered strategic. Neither were instances in which practitioners mentioned asking questions about a single prototype, as that was a baseline expectation during research design. These types of excerpts failed to include deliberateness and reasons behind choices, while still aligning with prior work demonstrating ways in which prototypes can be intentionally used as tools, but also unintentionally act and influence social interactions [14]. However, the research questions guiding this work focused particularly in the intentional actions (i.e., strategies).

Some uses of the strategy "*Show a single prototype to the stakeholder*" consisted of validating the selection of a concept that was informed by prior engagements with stakeholders using multiple prototypes, narrowing from a broader set of prototypes, making a recommendation, or demonstrating a potential incremental value to stakeholders. The fact that

the actual strategy "*Show a single prototype to the stakeholder"* had a greater prominence in the automotive domain as shown in Chapter 3 could have to do with the participants' constituting the sample and their projects. Multiple participants worked in the early stages of sub-component design and innovated within narrowly bounded or highly constrained problems, designed mostly incrementally, and made sure that any design work integrated with the work of other sub-systems and sub-component teams. Presenting a single prototype strategically to stakeholders seemed to anchor these engagements around the design concept itself, to have a focused conversation on design details, and seems to suggest a confirmatory use of a prototyping strategy. This confirmatory use of a strategy is a notable departure from many other front-end prototyping strategies defined in Chapter 2 which tended to be used in information elicitation contexts in more exploratory ways.

The intentional use of a single prototype with stakeholders during the earliest stages of design seemed better suited to have narrowly focused conversations around design details, to validate prior choices prior to fully committing to a concept, or in narrowly bounded "front-ends." Beyond those uses, the appropriateness of a single prototype to carry out front-end design activities should be carefully examined, as prematurely committing to a concept without exploring alternatives can lead to decision errors [114], which in turn can be difficult and expensive to rectify at later design stages.

5.3.2 Managing expectations through stakeholder engagement with early prototypes

In Chapter 2, the strategies were defined purposefully without prototype characteristics embedded in their names or definitions, as the same action could apply to functional and non-functional prototypes, among other characteristics participants used to describe their prototypes. The participants in both Chapter 2 and Chapter 3 extensively discussed the appearance of the

prototype and how it would be perceived when going to stakeholders for input. At times those concerns drove participants to use *"Brief the stakeholder about the project and the prototype(s) shown"* to explain the project status, expectations of participation, and the prototype and its state, e.g., why a prototype looked or worked how it did. This strategy was predominant in Chapter 2, and still salient and consistent in Chapter 3, which was not surprising given this method aligns with interviewing best practices. Practitioners' use of this strategy in these scenarios suggests also that they may intuit that stakeholders will perceive prototypes based in their own backgrounds and experiences, consistent with descriptions of how humans perceive design artifacts [112,176–178].

There were themes across studies about how participants handled their prototypes' appearance. The strategy *"Polish the prototype(s) shown to the stakeholder"* was particularly nuanced, and minimally used in the consumer products domain relative to automotive and medical devices as described in Chapter 3. We purposefully defined this strategy in Chapter 2 with respect to the actions being performed on the prototype for the purpose of stakeholder engagement. Notably, "fidelity" was not included in the name because aspects such as refining, and even "polishing" (figuratively) were also ways in which participants described handling prototypes to manage expectations while engaging stakeholders—who, for this strategy, they were often decision-makers. We did not code as *"Polish the prototype(s) shown to the stakeholder"* the participant excerpts mentioning the use of a high-fidelity prototype without deliberation or rationale. Instead, only instances in which the action was justified with respect to engaging a stakeholder were included in this strategy, and not simply the expected progression through design process stages. Across studies, increasing fidelity for stakeholder engagement was at times irrelevant to the front-end design questions participants had because the intended

product was still being defined. In Chapter 4, the first narrative captured this irrelevance when the practitioner described the prototypes that focused on the reclosing requirement questions as simple and rudimentary, as going beyond that "would have been an extra level of complexity to work that out and that wasn't important" at that point in her design process.

Interestingly, the opposite action to the prior strategy was found and defined as "*Lessen a prototype's refinement when showing it to the stakeholder*," although considerably less salient than every other strategy. In Chapter 2 practitioners moved from CAD to hand-drawn sketches which they perceived got them more and more genuine feedback. Practitioners also made non-defining features of a prototype (like a handle) purposefully less refined relative to other parts so the conversation flowed to the refined aspects, among other examples. The strategy was among the least used in Chapter 2 and Chapter 3, and used to navigate office politics in Chapter 4 with stakeholders internal to the company but external to the design team. While this strategy might not represent an efficient use of resources and gives the impression of doing redundant work, it might have still afforded some value to practitioners for managing expectations, perhaps downplaying the commitment to their ideas in an attempt to level the designer-to-subject or designer-to-partner dynamic.

Formally, the prototype characteristic of fidelity emerged from designing "user friendly" interfaces. Fidelity was defined as "the proximity of the prototype to the service as measured in the eyes of the user along the dimensions of breadth of features, depth of functionality, and similarity of interaction" [179], with famous debates to follow about the appropriateness of high and low fidelity prototypes [124]. Prototyping by increasing the level of fidelity has been documented in real design projects (e.g., [29]), and evidence suggests that doing so impacts the information value relative to resource expenditure in design projects [34]. In the latter study, the

authors argue low fidelity prototypes can support the elicitation of valuable information early on such as core concepts and user mental models, but cautioned that to keep higher fidelity prototypes economical, practitioners needed to be especially purposeful with the questions they asked, i.e., questions should increase in the level of detail in parallel with the design [34]. Based on the descriptions of fidelity in prototyping literature, it is a characteristic that exists relative to a selected concept, requiring a solidified product definition to begin with. The practitioner data across this dissertation's studies on their use of different methods for employing prototypes in ways that best suited their stakeholder engagement goals might point to a mismatch in design strategies to manage the front-end and the tendency to fixate on prototype characteristics closely tied to concrete and well-defined product definitions of selected concepts.

5.3.3 Engaging end-users with prototypes during front-end engineering design processes

In Chapter 4, the narratives predominantly illustrated the use of strategies with end-user stakeholders, which were classified within "prototype interactions:" "*Observe the stakeholder interacting with the prototype(s),*" *"Encourage the stakeholder to envision use cases while interacting with the prototype(s),"* *"Task the stakeholder with creating or changing the prototype(s),"* and *"Prompt the stakeholder to select prototypes and prototype features."* Additionally, strategies predominantly used by consumer products industry participants in Chapter 3 were particularly leveraged and well-suited for engaging end-users. These included some mentioned prior, as well as "*Introduce the prototype(s) to the stakeholder in the use environment,"* and *"Modify the prototype(s) in real time while engaging the stakeholder."* The closest relationships to these strategies are methods well established in fields such as Human-Computer Interaction, Human Factors and Ergonomics, and Co-Design (e.g., [4,77,102,180–182]). However, the design practitioners across studies were principal and senior engineers,

scientists, and designers, technology managers, designers, researchers, among other types of roles, all embedded within design projects. There seems to be a disconnect between the strong, rigorous technical feasibility orientation of prototyping research in engineering design and the wider set of methods employed in the design front-end for engaging end-users as evidenced by the participants in these studies. Further, functionality and usability are not the only important parameters for adoption and use of products [183], thus they should not be the only drivers for end-user engagement. For example, users will not adopt products that stigmatize them regardless of how well they function [184]. And while the prototyping strategies investigated in this body of work do not inherently enable the resource and power sharing conducive to co-design [185], they do represent a shift for engineering design. These strategies may be particularly suitable to explore, uncover, and impactfully address user needs, and an important incremental step towards earlier and more fruitful user involvement in engineering design processes.

In summary, three overarching themes connect the studies in this dissertation. These themes relate to goals practitioners sought to achieve through the use of prototyping strategies for stakeholder engagement. Within the overarching themes, this section discussed studies with respect to each other and with respect to the broader literature which has implications for design practice and education.

5.4 Implications

This work has implications for design practice and education. The prototyping strategies designers used to intentionally engage stakeholders during front-end design supplement traditional prototyping methods and best practices. Current engineering curricula development of prototyping strategies have been focused on evaluating ideas in the back end of design. These newly identified strategies can be used in front-end engineering design processes by both novices

and experienced design practitioners who want to become more "human centered" by grounding design in actual user needs balancing multiple stakeholders' priorities. The nuance and emphasis on specific prototyping actions within front-end design projects is a unique addition to existing human-centered design methods and frameworks such as the desirability lens in the Prototyping for X framework [100], the prototyping-related ideation methods in the IDEO Human-Centered Design Guide [105], the communication strategy of getting feedback using prototypes in the Prototyping Canvas [143].

The presented strategies focus on the elicitation of unmet needs, preferences, information, and priorities of stakeholders who are not directly involved in doing design work, addressing a research gap in prototyping strategies for exploration. The use of the strategy, *"Show the stakeholder multiple prototypes concurrently,"* seemed to support divergence, potentially contributing to informal mechanisms to find new product concepts which can support innovative outcomes [53]. Ultimately, considering multiple ideas during the front-end can help reduce risk in concept selection decisions [12], but as this work suggests, using multiple prototypes intentionally with stakeholders during front-end work may also be a meaningful mechanism for increased participation through design decision-making. The greater inclusion of multiple stakeholders' perspectives in engineering design may be important for improving organizational cultures by sharing ownership of the design beyond the core design team [57], and integrating outside perspectives so critical for successful project outcomes [7,184].

Current practices of prototyping towards an integrated technological solution might be tied to traditional prototype definitions that frame them as approximations to intended, implementation-ready design solutions (e.g., [24,25,29,33]). However, as more expansive prototype definitions are adopted (e.g., [14,28]), more expansive characteristics must be used to

describe prototypes. In other words, what is a high-fidelity prototype of a flexible product definition during the front-end? As practitioners' reports illustrated, they often boost or downplay their prototypes based on the expected stakeholder interaction, with special consideration to the anticipated reactions of stakeholders they engaged. While strategically polishing prototypes had a quality of mitigating irrelevant topics from emerging in conversations, so did lessening when non-defining features for the conversation were intentionally made appear unfinished. Often, practitioners sought to bring attention to the core merit of the idea, rather than the executional details of the prototypes. Bringing attention to specific aspects such as the core idea merit is a theoretically-supported notion: prototypes can reveal or manifest aspects of a design, and filter or leave out others [151]. It should be noted that high-fidelity prototypes of unique ideas have a tendency to be perceived as less risky than low fidelity versions [186], so the appropriateness of a high-fidelity prototype when a product definition is changing may be inadequate to convey actual risk to stakeholders, leading to potentially misaligned expectations. Beyond the expected progression of design concepts in a design process, careful consideration should be given to how a prototype offers affordances, and especially under which circumstances (i.e., what strategies for stakeholder engagement unlock that affordance?).

While design tasks are typically distributed by areas of technical expertise, it is very challenging to design products and systems grounded in human needs while situated as removed from a problem during the creation of design solutions. Engaging end-users through the use of prototypes is a central tenet of human-centered design processes [13,150,187], but becomes critically important when designers' own experiences are drastically dissimilar to end-users. Multiple medical device design practitioners in Chapter 2 discussed their engagement with end-

users ranging from patients to physicians to nurses, as did consumer product industry design practitioners and a subset of automotive industry practitioners in Chapter 3.

Costanza-Chock [188] posits that designers conceptualize imagined users with shared lived experiences. Given the demographics in design-adjacent fields (e.g., technology, innovation) in the United States, those imagined users tend to be "(cis)male, White, heterosexual, able-bodied, literate, college educated, not a young child and not elderly, with broadband internet access, with a smartphone" [188]. Needs of others who depart from this archetype tend to be overlooked and not designed for [188]. The use of that archetype as the default for all lived experiences has led to consequences ranging from systemic erasure to potentially unsafe situations [188]. Examples from product design involving unsafe situations for people with marginalized identities are: pulse oximeters [189], location tracking devices [190], and smart home devices [191]. Engaging end-users with prototypes can help designers catch these limitations before deploying resources and exposing end-users to possible harm and further marginalization. Importantly, intentionally engaging end-users with prototypes can also be used to identify areas of intervention to address overlooked needs, as design teams have done e.g., when designing adaptive kitchen tools for varied dexterity function [192]

While some research has described how novice and expert designers compare when doing design tasks, the studies in this dissertation sought to describe the methods and intentional techniques of design practitioners to narrow the gap between novice and experienced skillsets. This work responds to prior research describing student prototyping and stakeholder engagement approaches [35,116,156,171,193,194], with roots and ramifications in engineering pedagogy. The case narrative research method supporting the construction of individual story narratives afforded three important contributions for design education. First, placing the strategies in the

context of a specific project took them from abstract strategy to concrete application, potentially mitigating novices' tendency to problem-solve by trial-and-error [18]. Second, having such concrete details in constructed narratives offered analytic insights into practitioners' overarching approaches to engaging with stakeholders. The findings were then available to synthesize into different components in a general purpose prototyping tool for engaging stakeholders during early design. Lastly, while we have not yet investigated the impact of story narratives in student learning, their application may be promising in educational contexts to encourage the development of self-efficacy beliefs. Self-efficacy is an individual's own understanding of their capacity to produce a particular outcome [195]. Because students can view story narratives showing real experiences in the field, they may build an important source of self-efficacy through vicarious models (per Bandura [195]); e.g., seeing someone succeed equips observers of the behavior with the belief that they, too, can succeed.

These strategies have already had direct application in teaching students in curricular and co-curricular teams at the University of Michigan through the Center for Socially Engaged Design (C-SED). The prototyping strategies identified align with two of the central tenets of socially engaged design: understanding people and context, though more research is needed to integrate them with self-reflection. The work on the development of these strategies in engineering pedagogy is aligned with the SED process model [196] used across engineering senior design classrooms and educational programs at the University of Michigan. The research presented in this thesis aids in creating engineering methods and practices where equal weight can be given to the social and technical dimensions of engineering design work.

5.5 Future work

This dissertation explored and defined prototyping strategies to engage stakeholders during the front end of design. These exploratory studies were based in semi-structured interviews with design practitioners. Thus, more research is needed to validate these findings using different methods. Observation-based studies of actual stakeholder engagements in practice can be used to triangulate prior study findings, as well as to outline actual outcomes of stakeholder engagements with prototypes and continue refining prototyping strategies and their definitions. Another possible research direction to address the transferability and external validity of the findings is investigating the identified collection of strategies with a larger participant sample using semi-structured and structured interviews, or even survey instruments with participants across the design domains studied and other areas.

Future work can also focus on investigating individual prototyping strategies in a controlled setting to gain a better understanding of the outcomes of using the strategies in a given use scenario. Additionally future work may include the stakeholder's perspective in the use of strategies and how they experience being engaged with prototypes as well as how they perceive different strategic approaches. This work might help mitigate previously identified challenges, for example, to meeting medical device human factors standards such as designers' perceived mismatch in user expectations of participating in industry research, conflicting user opinions, and user creativity [107].

Lastly, more work might be needed to understand the use of story narratives for design education and its impact in novice designers' perception of prototyping to engage stakeholders, their thought processes, behaviors, and design outcomes. Future work can continue the development of pedagogical materials based in evidence from design practice, including the

prototyping tool presented in Chapter 4. Formal and informal rounds of feedback can be used to continue the development of the tool. Iterations based in findings should go in hand with a better understanding of this tool's contexts of use (e.g., curricular, co-curricular, entrepreneurial projects). A pilot study for the tool with potential workshop, training, and facilitation materials might be warranted to continue expanding the impact of this work. In addition to this tool, more work might be needed to integrate the strategies into existing frameworks for engineering design and human-centered design.

5.6 Conclusion

Prototyping is a powerful method for evaluating distinct aspects of engineering designs; however, expanding their use to the early stages of design allows an exploration of stakeholder needs, values, and priorities. The use of prototyping during front-end design work was found to rely on intentional, goal-driven use following a common set of strategies. This dissertation encompassed a qualitative approach which enabled the identification of 17 prototyping strategies to engage stakeholders during front-end design used by design practitioners across engineering design domains. Further, detailing their use within specific projects as described by practitioners uncovered rich information about the purpose of their use to inform design. A key to their effective use is their role in drawing out stakeholders' expectations for products, allowing designers to deliver design work that centers their needs and priorities. The findings include materials and a tool for engineering education about front-end prototyping for stakeholder engagement, applying a new understanding of front-end design process to benefit students and practitioners. By centering stakeholders in front-end design processes, intentional prototyping to engage stakeholders offers an expanded understanding of human needs, forming a basis for more inclusive design in engineering.

Appendix

Appendix A

Interview protocol: sample questions

- Can you select a project that you would say is the best example of a project you worked on where you used prototypes in the design front-end to engage stakeholders and briefly, describe what was the goal of that project?
- Who were the stakeholders you engaged during your project?
- Could you go over the different types of prototypes you used during the front-end phases of the project to engage with stakeholders?
- How did you choose which type of prototype to make to engage with stakeholders? Can you tell me more about the reasons for using this particular prototype with this stakeholder?
- Thinking about the prototypes you used to engage stakeholders, what were the purposes or goals of the prototypes? (i.e., what were you trying to accomplish)
- What was the role of the stakeholder in meeting that goal?
- Can you tell me how you used these prototypes to engage with the different stakeholders? This time I am asking you to describe the interactions during the engagements using prototypes with stakeholders in more detail. Go over all stakeholder types.
- What made an engagement with stakeholders using prototypes easy? What made an engagement challenging?
- What strategies have you used to make the interaction easier and mitigate what is hard?
- Could you tell us about a time when engaging stakeholders with prototypes supported problem identification or definition?
- What prototyping approaches were effective to learn more about that particular problem?
- Could you tell me about a requirement that was informed by the use of a prototype(s) with stakeholders; one that you might not have uncovered had you not had the prototype?
- What, if any, idea generation activities with stakeholders and prototypes took place in your project?
- In the project you described, did you use prototypes to select concepts/ filter out ideas with stakeholders? How did you use prototypes with stakeholders for concept selection?
- Are there any other activities that you would consider part of front-end design where you used a prototype to engage with stakeholders that we didn't talk about yet?
- To what extent was the use of prototypes with stakeholders more relevant for one design stage versus others?

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