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Prototyping Strategies to Engage Stakeholders During Early Stages of Design: A Study Across Three Design Domains

Using prototypes to engage stakeholders during front-end design activities is crucial for successful design outcomes. 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 of those 17 strategies were used by industry practitioners across the three domains, and five of those 17 strategies were used by practitioners from the medical device domain and either the automotive or consumer products domain. The descriptions and in-context examples of prototyping strategies used to engage stakeholders during front-end design can guide the design strategies of both experienced and novice designers. [DOI: 10.1115/1.4056815]

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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 [1], which hinges on appropriately defining and addressing stakeholder needs. Engaging stakeholders—people who impact and are impacted by design decisions and outcomes—with a shared medium, such as a prototype, helps designers and stakeholders discuss values and priorities by enabling feedback and facilitating effective communication [2,3]. However, prototyping in engineering design curricula tends to emphasize later design 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 [4,5]. Even though prototyping is essential for testing design performance or how a specific design meets specifications during back-end design activities (e.g., verification testing) [6], these design activities are distinct from the front end of design. Front-end design activities include, for example, initial problem identification, needs finding, early concept generation, and concept development [7–9]. During the front end of design, problems, opportunities, requirements, specifications, and ideas are emergent and still being defined [10]. These complex, ambiguous, and iterative design activities can be 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 such that they span a

design process or back-end design activities [11–15]. At the same time, limited literature describes prototyping strategies specifically associated with the front end of design [16,17]. Some design research has considered how prototyping for stakeholder engagement is influenced by the stakeholder engaged and question asked with the prototype [18], the designer's prior knowledge of the design space, and the product's degree of user interaction [19]. Additionally, while not specific to prototypes, research has shown that product type, product domain, and company structure may shape the types of stakeholders designers include in their design processes and to what level these stakeholders are involved [20]. 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 [21]. In mature organizations or product lines, design is often approached more incrementally, with gradual, cumulative changes made to existing products [22]. 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 [23]. Per Schrage [23], these cultures may dictate the iterative use of prototypes (i.e., prototyping-driven specification development), or in contrast, using prototypes as an “end product of thought” (i.e., specification-driven prototype development).

Some recommended prototyping approaches might apply across multiple contexts. For example, some studies have found commonalities in prototyping approaches while sampling across various contexts [2,24,25]. However, the extent to which prototyping strategies are used across disciplinary domains—particularly for front-end uses with stakeholders—is unknown, as are the nuanced applications of these strategies depending on the context. Therefore, this study aimed to investigate prototyping strategies used to engage stakeholders during the design front end of three product domains

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(automotive, consumer products, and medical devices) and to describe patterns and distinctions in strategies used across designers' project contexts.

Background

Prototyping strategies in the engineering design literature have been defined as "a set of choices that dictate actions" in a broader product development process [26]. Prior prototyping strategies research has focused on planning for specific applications of prototypes based on different factors [19]. Such planning may include using specific techniques to achieve particular objectives [6,27]. For example, in some prototyping efforts, it may be appropriate to employ the technique of isolating sub-systems for the objective of reducing total time [6]. Further, other research has emphasized that a prototyping strategy contains decisions about prototyping media, materials, manufacturing, tests, and iterations in a product development process [28]. 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 engineering design. Importantly, engaging stakeholders with prototypes early in design processes has been attributed to project and organizational success [29,30].

Prototyping Strategies for Stakeholder Engagement in Engineering Design. Several studies have explored the role of prototypes to support communication with stakeholders in engineering design [3,31]. Research has shown how different prototype characteristics affect the information gathered [32], in addition to how the stakeholders' background and the type of questions they are asked affects the feedback they give on prototypes [18]. Theory that describes the dynamic ways in which prototypes influence social interactions has been established [2,3,33,34], 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 use to engage with stakeholders during front-end stages [17,35]. An interview-based research study [17] that sampled medical device design practitioners working in corporate and global health settings described 17 strategies for using 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 that prompted meaningful dialogue and helped practitioners gather information to develop requirements and specifications and to evaluate early solution ideas. Further work demonstrated that practitioners working in global health settings adapted the same strategies from the broader sample depending on the context of their projects [35]. For instance, some practitioners adapted strategies to tackle stakeholder remoteness [36], 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.

Prototyping Across Different Dimensions of Context. While there are commonalities in product development processes across domains, there are also differences based on the unique context of the organization performing the design work and the specific design project challenges [25]. The concept of a "prototyping culture"—an organization's structures and processes to create prototypes and manage prototyping efforts [23]—is anchored on a similar idea that multiple aspects and dimensions of context affect design outcomes. Using different companies as cases, Schrage [23] 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, and suppliers).

Jensen et al. [32] described relationships among prototype functionality, stakeholder involvement, and requirements elicitation. They suggested that the designers' organizational cultures around prototyping can support or hinder their ability to uncover latent requirements and needs. Further, Elverum et al. [19] 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 the 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, but successful outcomes. For instance, the project with greater prior knowledge had more focused, mainly digital, and less resource-intensive prototyping approaches.

Specifically, how prototyping strategies are used based on such contextual factors to engage stakeholders remains to be explored. Similarly, as decisions about strategies to use prototypes depend on many aspects of the context, front-end design decisions 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 influence how the design front end is carried out across companies [21]. 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 applied may vary according to context.

Methods

Prior research identified 17 prototyping strategies that medical device design practitioners used to engage stakeholders during front-end design activities [17]. 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?

Participants. 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 17 strategies originated from a broad medical device practitioner sample that included global health design practitioners, which were not included in this study. In order to be consistent with the participants from the other two design domains included in this study, only medical device practitioners working in multinational companies and startups were included in this analysis. Eligible participants were required to (1) have worked in a design role (e.g., technology, product design, design research, and 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 materials 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 exempt, and all participants provided written consent to participate in the study. Participants were given the opportunity to review the interview excerpts quoted in the manuscript. Some provided edits for clarity and accuracy, consistent with member-checking practices. Participant information is summarized in Table 1.

Data Collection. We used 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 [17]. 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 the 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, and adapting terms so they translated across domains.

Definitions of concepts used throughout the interview such as front-end design, product, prototypes, and stakeholders were provided at the beginning of the interview, which are included in Appendix A. 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 B.

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

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 using prototypes during front-end design activities. We deductively analyzed the data according to an existing codebook from prior work (Table 2) as well as inductively analyzed the data 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 [37,38]; thus, the technique was deemed appropriate for assessing the transferability of the prototyping strategies used by medical device design practitioners 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 [38] and was appropriate for seeking strategies beyond the ones previously identified. Using a full transcript as the unit of analysis, two study team members, with previous qualitative data analysis experience, determined the presence or absence of each previously identified strategy and marked any potential additional strategies throughout the interview transcripts.

Coding was performed first independently by each of the two study team members with a subset of transcripts. Then the two members compared intermediate results, made revisions, and then

Table 1 Participant information

	Product type, Company type	Design exp. (years)	Job tenure (years)	Sex	Ethnicity	Education	Age
AU1	Vehicle performance sub-system, large manufacturer	6	2	F	Hispanic/LatinX	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
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
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	Catheterization lab and cardiac surgery devices, large manufacturer	25	7	M	NC	Master's	55
MD8	Catheterization lab and 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	Catheterization lab device, startup	3	1	M	NC	Bachelor's	25
MD12	Implantable devices, large manufacturer	12	20	F	NC	Master's	47

Note: Ethnicity data were not collected for the medical device domain participants (noted by "NC"), and other participants chose not to provide their ethnicity (noted by "NP").

AU, automotive; CP, consumer products; MD, medical device.

Table 2 Codebook for data analysis (from Ref. [17])

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)

discussed the codes with the full research team prompting iteration in the codes and language to describe the codes. After these rounds, an 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. The agreement was 71% across seven transcripts. Disagreements were resolved through discussion for those seven transcripts. The primary disagreements included: determining when a strategy was used intentionally (e.g., observe versus simply witnessing), and differentiating among 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.” Clarifications were made to the codes as disagreements were resolved. Then, coding for strategies was performed by a single coder. The numbers of participants in each domain that described using each prototyping strategy during their interviews were tabulated.

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 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 ... we were looking at building different concepts of basically one design, and that was also really important to [...] 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 [having] less leg room, or something like that if you do this [concept], 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.

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 described 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 [17].

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.

Strategies were defined as high-level actions involving specific instances of practitioner interactions with stakeholders using one or more prototypes. Because prototypes were defined broadly

from the onset of the interview, strategies could be implemented using different types of prototypes and varying fidelity levels to explore different systems and sub-systems. In other words, strategies were not defined with respect to particular types of prototypes or stakeholders. For example, the following excerpts illustrate three diverse applications of the strategy *Show the stakeholder multiple prototypes concurrently*. Participant AU2 shared, “it is common practice to share multiple physical and digital models when considering different design options,” referring to the possibilities of using the strategy with internal stakeholders. Participant CP2 conveyed the use of the same strategy with existing products as prototypes to engage with external stakeholders: “When we started the project, we showed prototypes even in the need discovery phase because we [had not] done a single bit of design [work] and we [had not] even decided what the needs were. You know what our prototypes were? A broad range of current [products] ... so we used current product offerings that had significant design differences as the prototypes.” Participant CP3 discussed building 3D physical prototypes to show stakeholders: “...we created a range of prototypes which were different ways of getting the [product] into the [location] without touching it. And they got the consumers to do it both with dry hands and wet hands.”

Participants from the automotive and consumer products domains described using 12 of the 17 strategies. Five of the 17 strategies were used by participants from two of the three domains. Automotive and medical device participants used three of the five strategies, while consumer products and medical device participants used two. We summarize these frequencies by strategy and participant domain in Table 3.

Participants from particular domains described the use of specific strategies for the projects shared with different frequencies than those in other domains. For example, more automotive industry participants than participants from the other two domains described using the following strategies: *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, affected their choices when using prototypes with stakeholders.

Strategies With Similarities in Use Scenarios Across Domains. Our findings 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 participant excerpts to describe their use scenarios.

The strategy *Brief the stakeholder about the project and the prototype(s) shown* was similarly used by eight participants across domains to establish expectations for participation and engagement with stakeholders when showing prototypes, to build rapport, and to 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 involved 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 provided by 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 the affordances such that she just naturally knows how to use it. (CP2)

Table 3 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
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 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 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, [...] we will have to explain every minute detail, we will have to go [into] every minute detail of the design, [and] how it will work. (AU6)

The second strategy used similarly across use scenarios was *Show the stakeholder supplemental materials related to the concept to complement the prototype*, which also had similarities in use 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 to elaborate on the details of a prototype. This use scenario was 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 demonstrating form and function, physical prototypes accompanied by presentation slides or sketches and drawings, among others. AU3 summarized the numerous possible combinations by stating how they used, “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 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 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 look-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 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 seeking an early investment in the project:

We developed minimum viable prototypes for in-home use and in-store checks to see if this container would be engaging at shelf, and evaluate if this container would solve key issues people were having with current packages. Through observation and in-store interviews, we generated data that helped us provide evidence to our investors—

the managers of the division to which this package would be commercialized—to approve the next phase of development for our project. (CP5)

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 the emotional context associated with interacting with the vehicle's buttons during an emergency situation:

For the one project I was working on ..., 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 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:

CAD data is relatively lightweight, compared with rendered or other data sets that have additional functionality, thus making it easier and more efficient to modify. CAD data can provide the initial starting point for collaboration with multiple stakeholders, such that basic functionality can be easily communicated and revisions can be made quickly. When considering finer details, data enhancement is typically required, thus making the data more complex and requiring more manhours to refine the data. However, the additional investment allows deeper collaboration and enhanced visualization with a realistic representation. At this level of refinement, data can be shared in a fully immersed virtual environment, giving stakeholders the ability to make accurate decisions. (AU2)

Strategies With Varying Use Scenarios by Domains. Our findings 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 conducted 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 [current] 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 from 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 where 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. 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 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)

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 [a cognac] bottle on display. And then, she pulled it down for us to get a look at. So this is a ... cognac bottle. 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 [that specific] 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." ... And then we would end up in their closets and when we're in their closets, I had to pack Post-it® [notes]. 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, Participant CP4's strategy is 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.

Discussion

In this study, we found that the previously identified prototyping strategies used to engage stakeholders during front-end design 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 [39,40] and other overarching themes that characterize design tasks and design problem spaces [41].

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 product 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 [42], 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 [43–45]. Further, previous research has demonstrated that design practitioners adapt methods in an opportunistic manner to serve their unique design goals [45]. 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 that some contextual considerations impact prototyping choices [3,18,19,35].

Further, the participant approaches 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 [46], 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 [45], 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 [24,47], engaging stakeholders with prototypes [48], and navigating complex or conflicting stakeholder information during front-end design activities [49].

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 on 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 earliest 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 [3].

Limitations of this study include the potential blurring of prototype-related activities with stakeholders associated with the early versus later 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 uses that moved into more back-end phases of design 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 participants. We acknowledge that designers with different backgrounds and personal and social identities from the ones recruited may leverage different strategies or do so in different ways than were revealed in this study.

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 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 are critical for design success.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Appendix A: Definitions Provided to Participants Prior to Starting the Interview

- We define the front-end phases as early design activities associated with problem identification, problem definition,

requirements and specifications development, background research, concept generation and concept development.

- In the scope of this interview we won't focus on prototype use during later phases of design such as during embodiment and/or detailed design phases, verification, validation, pre-production, production, launch and post-launch activities.
- We use the word product to refer to the designed object/artifact. The prototype can represent a process, a system, or a sub-component of the intended design.
- We consider prototypes to include mock-ups, CAD models, drawings, scenarios, and other representations of a design idea, a product or its use.
- We define a stakeholder as anyone who will affect or be affected by the intended design at any point of the design or development process, including end-users, customers, colleagues, manufacturers, clients, policy makers, technicians, operators, and so forth.

Appendix B: 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?
- 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.)
- Could you tell us about a time when engaging stakeholders with prototypes supported problem identification or definition?
- 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?
- 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?

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