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Using Practitioner Strategies to Support Engineering Students' Intentional Use of Prototypes for Stakeholder Engagement During Front-End Design*

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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.

Keywords: prototyping; stakeholder engagement; front-end design; design practice; engineering education

1. Introduction

Central to successful design processes is the involvement of stakeholders, including people who use, affect, or may be affected by design decisions and outcomes. Prototypes support communication, enabling designers to explain concepts, and importantly, to obtain feedback from stakeholders [1, 2]. Using prototypes to engage stakeholders, especially during the early, "front-end" stages of design, can facilitate iterative gathering and synthesis of stakeholder perspectives [3]. Prototypes can help elicit design information about stakeholders' latent knowledge and deepen designers' understanding of important needs [4, 5], both of which are key aspects of effective front-end design work [6, 7]. Engaging in early, exploratory prototyping during the design front-end supports designers in the development of successful design outcomes [8]. Although sources highlight the value of using prototypes in the earliest phases of design processes [9, 10], prototypes are commonly emphasized during back-end engineering design stages, and framed as tools to be used once solution concepts have been selected [11–14].

During the back end of design, both novices and experienced designers have been shown to recognize weaknesses in their designs via physical prototyping [15]. However, more experienced designers employ different approaches than novices do [16, 17], which have been characterized as "designerly ways" of thinking, acting, and being [18, 19]. Specific to prototyping, Hilton et al. [20] 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 [21–23]. In addition to design experience supporting strategic uses of prototypes, Elverum et al. [24] 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

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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 [25]. 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 [27]. Generally, engineering design textbooks emphasize prototyping as a specific stage of a design process, and as a tool for verification and validation purposes [11–14]. 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., [28–30]). 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 [31]. Other interventions have focused on the development of prototyping approaches to improve desired functional performance outcomes (e.g., Dunlap et al. [30], Camburn et al., [32, 33]) or the consideration of ergonomics and human factors in engineering product design (e.g., Ahmed and Demirel [34, 35]).

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 [36]. 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 [37]. 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 [38]. Additionally, the *Prototyping Planner* provides four steps to support novices in prototyping more purposefully and using prototyping results when making design decisions [39]. While this tool was successful in supporting novices to prototype purposefully, Hansen et al. (2020) 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 [39]. 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 [40] and gathering rich information about stakeholders' values and experiences [41]. 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.

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 [42]. Additionally, narratives can outline a storyline and human action, facilitating communication about the event or experience to the reader [43]. 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.

2.1 Participants

Three participants, who we call Elaine, Brian, and Robin (pseudonyms), were selected from an existing larger set of data collected from 36 design practitioners, including 22 participants from an earlier study [22]. 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 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 [22]. Based on this informal assessment, we opted to detail strategies that were not commonly named in engineering design texts (e.g., [11, 12]), and strategies that novice designers have been shown to rarely apply during front-end activities with stakeholders [25], e.g., to promote non-superficial engagements, to support problem scoping and requirements elicitation, and to identify broader contextual factors and usability problems.

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 elicit 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.

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 [42], 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 [22] 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.

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.

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 while 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.

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 subgroup 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.

Narrative #3: Robin

At the time of his interview, Robin was a senior program manager with 12 years of design experi-

ence 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. 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 engagements 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.

4.1 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 [1], that prototyping is not a discrete design stage, but an ongoing design activity. In Table 1, 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.

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

Table 1. Stakeholder engagement strategies presented in the story narratives

Strategy category	Strategy	Description	Narratives that included the strategy
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

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 [23].

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.

4.1.1 Focus 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 [27, 29]. 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 [44], and facilitate discussion with stakeholders about high-level ideas [5]. 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., [35, 36]), 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.

4.1.2 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 [22]; seven 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

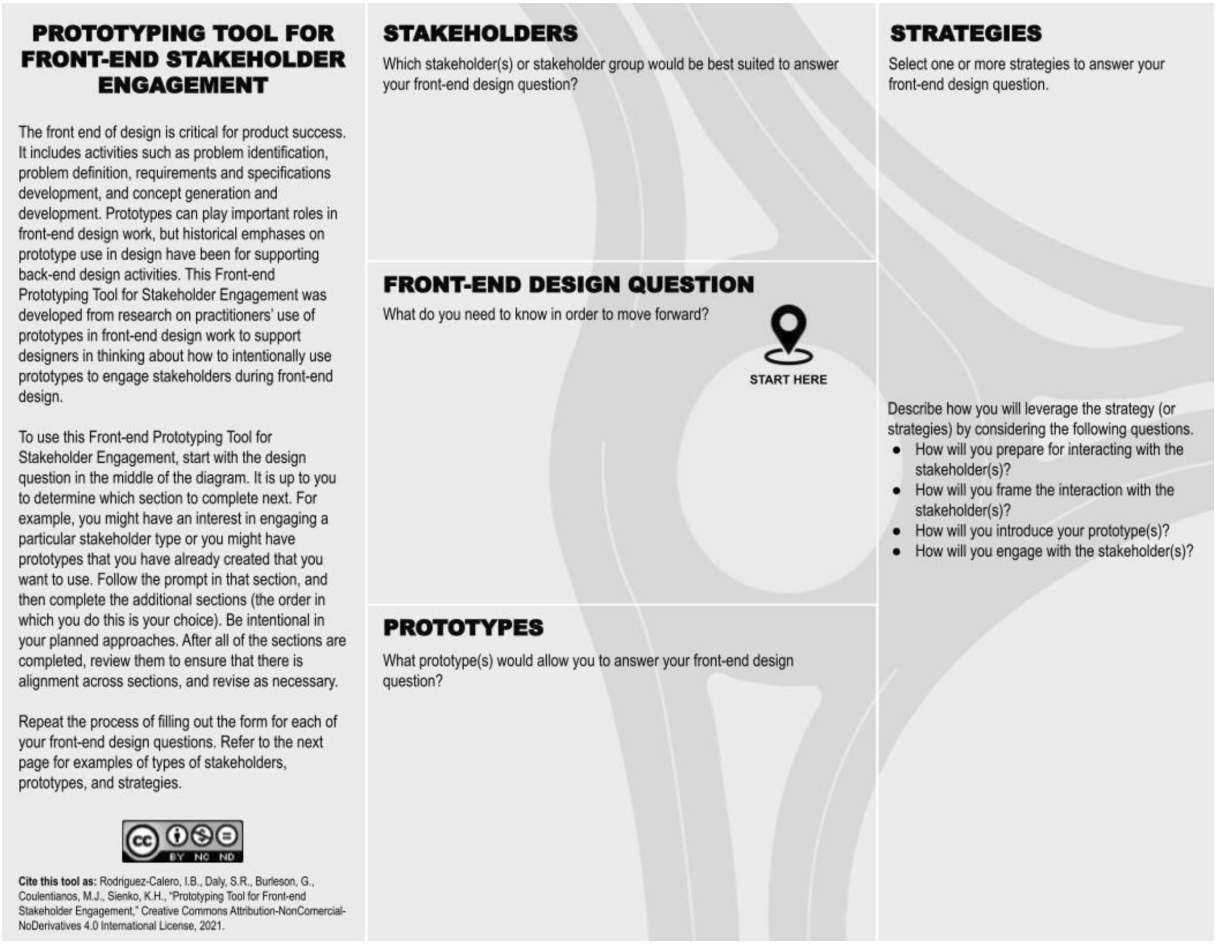

Fig. 1. Considerations for stakeholder engagement using prototypes during front-end design as presented in [46].

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 [45]. 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 [41].

Engineering educators can share the strategies summarized in Table 1 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.

4.1.3 Plan the Stakeholder Engagement around a Specific Question to Answer with the Prototype

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 [46], and show this tool in Fig. 1.

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.

4.1.4 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.

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.

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References

1. C. A. Lauff, D. Kotys-Schwartz and M. E. Rentschler, What is a prototype? what are the roles of prototypes in companies?, *Journal of Mechanical Design*, **140**(6), 2018.
2. C. A. Lauff, D. Knight, D. Kotys-Schwartz and M. E. Rentschler, The role of prototypes in communication between stakeholders, *Design Studies*, **66**, pp. 1–34, 2020.
3. R. G. Cooper, The drivers of success in new-product development, *Industrial Marketing Management*, **76**, pp. 36–47, 2018.
4. M. B. Jensen, C. W. Elverum and M. Steinert, Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures, *Design Studies*, **49**, pp. 1–31, 2017.
5. E. Tiong, O. Seow, B. Camburn, K. Teo, A. Silva, K. L. Wood, D. D. Jensen and M. C. Yang, The Economies and Dimensionality of Design Prototyping: Value, Time, Cost, and Fidelity, *Journal of Mechanical Design, Transactions of the ASME*, **141**(3), p. 031105, 2019.
6. A. K. Gupta and D. L. Wilemon, Accelerating the Development of Technology-Based New Products, *Journal of Product Innovation Management*, **7**(4), pp. 323–335, 1990.
7. A. Khurana and S. R. Rosenthal, Towards holistic 'front ends' in new product development, *Journal of Product Innovation Management*, **15**(1), pp. 57–74, 1998.
8. A. Häggman, G. Tsai, C. Elsen, T. Honda and M. C. Yang, Connections Between the Design Tool, Design Attributes, and User Preferences in Early Stage Design, *Journal of Mechanical Design*, **137**(7), p. 071101, 2015.
9. T. Kelley, Prototyping is the shorthand of innovation, *Design Management Journal (Former Series)*, **12**(3), pp. 35–42, 2010.
10. A. Savoia, *Pretotype it*, 2nd edn., October 2011.
11. K. T. Ulrich and S. D. Eppinger, *Product design and development*, McGraw-Hill, 2008.
12. G. E. Dieter and L. C. Schmidt, *Engineering design*, 5th ed. New York, NY: McGraw-Hill, 2013.
13. G. Pahl, W. Beitz, J. Feldhusen and K. H. Grote, *Engineering design: A Systematic Approach*, Third Edit. London: Springer, 2007.
14. C. L. Dym and P. Little, *Engineering design: a project-based introduction*, 3rd ed. Hoboken, N.J., NJ: Wiley, 2008.
15. V. Viswanathan, O. Atilola, J. Goodman and J. Linsey, Prototyping: A key skill for innovation and life-long learning, in *Proceedings – Frontiers in Education Conference, FIE*, 2015.
16. C. J. Atman, R. S. Adams, M. E. Cardella, J. Turns, S. Mosborg and J. Saleem, Engineering Design Processes: A Comparison of Students and Expert Practitioners, 2007.
17. T. A. Björklund, Initial mental representations of design problems: Differences between experts and novices, *Design Studies*, **34**(2), pp. 135–160, 2013.
18. N. Cross, Designerly Ways of Knowing: Design Discipline Versus Design Science, *Design Issues*, **17**(3), pp. 49–55, 2001.
19. R. S. Adams, S. R. Daly, L. M. Mann and G. Dall'Alba, Being a professional: Three lenses into design thinking, acting, and being, *Design Studies*, **32**(6), pp. 588–607, 2011.
20. E. Hilton, J. Linsey and J. Goodman, Understanding the prototyping strategies of experienced designers, in *Proceedings – Frontiers in Education Conference, FIE*, pp. 1–8, Oct. 2015
21. M. J. Coulentianos, I. Rodriguez-Calero, S. R. Daly and K. H. Sienko, Stakeholder engagement with prototypes during front-end medical device design: Who is engaged with what prototype?, in *Frontiers in Biomedical Devices, BIOMED – 2020 Design of Medical Devices Conference, DMD 2020*, Apr. 2020.
22. I. B. Rodriguez-Calero, M. J. Coulentianos, S. R. Daly, J. Burridge and K. H. Sienko, Prototyping strategies for stakeholder engagement during front-end design: Design practitioners' approaches in the medical device industry, *Design Studies*, **71**, p. 100977, 2020.

23. I. Rodríguez-Calero, M. Coulentianos, S. R. Daly and K. H. Sienko, Single versus multiple prototypes: Medical device design practitioners' rationale for varying prototype quantities to engage stakeholders during front-end design, in *Frontiers in Biomedical Devices, BIOMED - 2020 Design of Medical Devices Conference, DMD 2020*, Apr. 2020.
24. C. W. Elverum, T. Welo and S. Tronvoll, Prototyping in New Product Development: Strategy Considerations, *Procedia CIRP*, **50**, pp. 117–122, 2016.
25. M. Deininger, S. R. Daly, K. H. Sienko and J. C. Lee, Novice designers' use of prototypes in engineering design, *Design Studies*, **51**, pp. 25–65, 2017.
26. C. Lauff, D. Kotys-Schwartz and M. E. Rentschler, Perceptions of prototypes: Pilot study comparing students and professionals, in *Proceedings of the ASME Design Engineering Technical Conference*, 2017.
27. S. Howe and J. Goldberg, Engineering Capstone Design Education: Current Practices, Emerging Trends, and Successful Strategies, in *Design Education Today*, Springer International Publishing, pp. 115–148, 2019.
28. M. C. A. Cooper, M. Anderson, C. Bruce, S. Dorman, D. Jensen, K. Otto and K. Wood, Mini-Design Projects in Capstone: Initial Design Experiences to Enhance Students' Implementation of Design Methodology, in *122nd ASEE Annual Conference & Exposition*, 2015.
29. T. Gurjar, Effects of a structured prototyping strategy on capstone design projects, 2015.
30. B. U. Dunlap, C. L. Hamon, B. A. Camburn, R. H. Crawford, D. D. Jensen, M. G. Green, K. Otto and K. L. Wood, Heuristics-based prototyping strategy formation: Development and testing of a new prototyping planning tool, in *ASME International Mechanical Engineering Congress and Exposition, Proceedings*, **11**, 2014.
31. M. Yong Ze Siin, S. N. Namasivayam, M. H. Fouladi, M. A. Mohd Zali, L. C. Quen and M. C. Hang, Utilisation of the conceive-design-implement-operate framework in a mechanical engineering capstone project, *International Journal of Mechanical Engineering Education*, **48**(1), pp. 32–54, Jan. 2020.
32. B. Camburn, B. U. Dunlap, R. Kuhr, V. K. Viswanathan, J. S. Linsey, D. D. Jensen, R. H. Crawford, K. Otto and K. L.Wood, Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment, in *Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2013*, Aug. 2013, pp. 1–10, 2013.
33. B. Camburn, B. Dunlap, T. Gurjar, C. Hamon, M. Green, D. Jensen, R. Crawford, K. Otto and K. Wood, A Systematic Method for Design Prototyping, *Journal of Mechanical Design*, **137**(8), pp. 81102–81103, 2015.
34. S. Ahmed and H. O. Demirel, A Conceptual Prototyping Framework for Integrating Human Factors Early in Product Design, in *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, Nov. 2020.
35. S. Ahmed and H. O. Demirel, A pre-prototyping framework to explore human-centered prototyping strategies during early design, in *Proceedings of the ASME Design Engineering Technical Conference*, Nov. 2020, **8**, 2020.
36. J. Menold, K. Jablokow and T. Simpson, Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design, *Design Studies*, **50**, pp. 70–112, 2017.
37. J. Menold, K. Jablokow and T. Simpson, The Prototype for X Framework: Assessing Impact on Self-Reported Prototyping Behavior of Student Designers, *Journal of Mechanical Design*, **141**(4), p. 042001, Jan. 2019.
38. C. Lauff, J. Menold and K. L. Wood, Prototyping Canvas: Design Tool for Planning Purposeful Prototypes, *Proceedings of the Design Society: International Conference on Engineering Design*, **1**(1), pp. 1563–1572, 2019.
39. C. A. Hansen, L. S. Jensen, A. G. Özkil and N. M. Martins Pacheco, Fostering Prototyping Mindsets In Novice Designers With The Prototyping Planner, *Proceedings of the Design Society: DESIGN Conference*, **1**, pp. 1725–1734, May 2020, doi: 10.1017/dsd.2020.132.
40. I. Mohedas, S. R. Daly and K. H. Sienko, Design ethnography in capstone design: Investigating student use and perceptions, *International Journal of Engineering Education*, **30**(4), pp. 888–900, 2014.
41. R. P. Loweth, S. R. Daly, A. Hortop, E. A. Strehl and K. H. Sienko, A Comparative Analysis of Information Gathering Meetings Conducted by Novice Design Teams Across Multiple Design Project Stages, *Journal of Mechanical Design*, **143**(9), 2021.
42. M. Q. Patton, *Qualitative research and evaluation methods: Integrating theory and practice*, 4th ed. Sage Publications, 2015.
43. M. B. A. Miles, M. Huberman and J. Saldaña., *Qualitative data analysis: A methods sourcebook*, 3rd ed. Thousand Oaks, CA: Sage Publications, 2014.
44. E. Gerber and M. Carroll, The psychological experience of prototyping, *Design Studies*, **33**(1), pp. 64–84, 2012.
45. J. Menold, C. Berdanier, C. McComb, E. Hocker and L. Gardner, 'Thus, I had to go with what i had': A multiple methods exploration of novice designers' articulation of prototyping decisions, in *Proceedings of the ASME Design Engineering Technical Conference*, pp. 1–11, 2018.
46. I. B. Rodriguez-Calero, S. R. Daly, G. Burleson, M. J. Coulentianos and K. H. Sienko, Prototyping Tool for Front-end Stakeholder Engagement, Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, 2021. https://dalyre-search.engin.umich.edu/wp-content/uploads/sites/237/2021/10/prototyping_tool_for_front-end_stakeholder_engagement.pdf, Accessed 21 October 2021.

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