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A Comparative Analysis of Student Perceptions of Recommendations for Engagement in Design Processes

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Engineering designers are tasked with complex problems necessitating the use and development of various supports for navigating complexity. Prescriptive design process models are one such tool. However, little research has explored how engineering designers perceive these models' recommendations for engagement in design work. In this exploratory study, we analyzed data from individual semi-structured interviews with 18 mechanical engineering students to identify participant perceptions of design process models. As many design process model visualizations lack explicit attention to some social and contextual dimensions, we sought to compare perceptions among two models drawn from engineering texts and one model that was developed with the intent to emphasize social and contextual dimensions. We identified perceptions of the recommendations from the design process models related to starting and moving through a design process, gathering information, prototyping, evaluating or testing, and what they should consider. Participant perceptions across the three process models suggest different design process models make perceptions of certain recommendations more salient than others. However, participant perceptions also varied for the same process model. We suggest several implications for design education and training based on participant perceptions of the process models, particularly the importance of leveraging multiple design process models. The comprehensive descriptions of participant perceptions provide a foundation for further investigations bridging designers' perceptions to intent, behavior, and, ultimately, design outcomes.
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Keywords: design courses and curriculum, design education, design methodology, design process, design representation, design theory, design theory and methodology, design visualization, product design, user-centered design

Introduction

Engineering designers rely on various forms of support, such as design tools, training, and process models, to address complex and multifaceted design problems. Designers, from novices to experts, leverage design process models—particularly prescriptive process models—to support systematic approaches to their design work. Systematic approaches are especially helpful in situations where failure can have grave consequences, where there is a high probability of being wrong, or where problems are complex [1]. Novice designers, with limited experience and a higher likelihood of making mistakes [2], are especially well-situated to benefit from such models—as intentional practice is crucial in developing expertise [3]. Furthermore, research supports the efficacy of models as pedagogical tools across different domains, from supporting students' understanding of atoms and molecules [4] to fostering scientific creativity [5].

While numerous design process models have been developed to support design training and practice, we do not have a deep understanding of their impact on model users. For example, related research describes understandings of process models based on "throwaway comments of interviewees and complaints of project managers" (p. 9) and informal follow-up discussions with design managers [6]. Thus, we cannot leverage knowledge of design process models' impact to support model users in choosing and using such models. The lack of research on the impacts of design process models on model users stands in contrast to the numerous studies in science literature that have investigated students' understandings after engagement with visual representations to inform pedagogy (e.g., [7–9]). Furthermore, while there is prior research on the visual representations of design process models, much of this work focuses on researchers' analysis of the visual representations (e.g., [10]). The use and development of design process models that align with recommended practices for user-centered

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design [11,12] should include the perspectives of model users, such as design practitioners, students, and educators.

Additionally, while it is crucial for mechanical engineers to incorporate social and contextual dimensions into their decision-making to avoid causing harm and also to better human welfare [13], many visual representations of design process models (e.g., [2,14]) lack explicit references to some of these dimensions. Understanding the guidance provided to designers, especially novice designers, by design process models and how the inclusion of social and contextual dimensions affects this guidance is essential. Therefore, we interviewed novice designers about three design process models known to be used in undergraduate engineering design education, including one that explicitly incorporated a range of social and contextual dimensions. The outcomes of this work can support design pedagogy and inform model users' selections and use of the design process models investigated.

Background

Design Process Models, Model Visualizations, and Model Classifications. Given the complexity of design [15] and the abstract nature of all models [6], there is no single comprehensive design process model. Further, process models are affected by model creators' priorities and representation affordances. Thus, evaluation of process models should focus on fulfillment of their intended purposes rather than trying to determine absolute "correctness" [6].

There are numerous ways to express a model, including graphically, mathematically, or in text [15]. Many design process models are represented with shapes, arrows, and text labels highlighting stages of and pathways through design work [14]. When using models that have a visual representation, some model users may draw on textual descriptions of a process in addition to the model's visual representation. However, the principle of salience for visual displays says that the most important information should be salient within a display [16–19]. Thus, following the principle of salience, a good visual representation of a design process model represents the most important parts the model creator wanted to emphasize. Additionally, the benefit of visualizations is reflected in their ability to be used as a map or guide for approaching design work. While a textbook may describe a design process model, in practice, an engineer will probably not have the time to reread all available text to review a model, but they can have a printout of the visual representation on their desk for quick reference.

One way to classify process models is whether they have prescriptive and/or descriptive aspects. Prescriptive models are "those that prescribe how the *design process* ought to proceed" [20], and descriptive models are those that focus on describing how design occurs in practice [20]. Importantly, a single design process model can have both prescriptive and descriptive elements [20,21]. Prescriptive design process models are a particularly important type of process model for supporting design practice as they necessarily aim to guide designer behavior.

Impacts of Design Process Models. Prescriptive design process models are developed to support communication within and across disciplines, prevent omissions in the process, enable education, and facilitate planning [22]. Process models are leveraged in industry projects to support planning a design process [23]. While more research evidence is needed to verify the assumption that following a prescribed process leads to better design outcomes [20,24], recent design studies suggest a connection between using a prescriptive design process model and quality design outcomes. Moraes and colleagues [25] introduced the "W-model" as a prescriptive design model for pre-college novices and found informed designer behaviors—defined by the Informed Design Teaching and Learning Matrix [26]—in student teams using this model. Another study on a freshman-level design-and-build course found a moderate-to-strong correlation between student teams' adherence to a prescriptive design cycle and client satisfaction for the most difficult project, leading the authors to suggest that the impact of prescriptive design cycles may be stronger for more difficult projects compared to simpler ones, as ad hoc solutions may satisfice in simpler projects [27].

Model Uses and Perceptions. In fields that utilize models, such as the sciences, scholars have outlined various roles models play in supporting processes and outcomes within the discipline. Models in science serve a multitude of purposes, including visualization, hypothesis formulation, critical analysis of ideas, examination of theories, and derivation of relationships [28–31]. In engineering, models are used in similar ways, including to emphasize key aspects of design processes (e.g., [32]), whether describing or prescribing design practice. While researchers have compared design models from academia and industry—based on aspects of the models such as stages included—by conducting literature studies and analyzing the models themselves (e.g., [10,22,33,34]), limited research exists on designers' perceptions of design process models. Eckert and Stacey [6] noted that the engineers and project managers they interviewed across several studies lacked awareness of diverse interpretations of models and assumed a single correct interpretation of the model [23,35,36]. The researchers found various interpretations of a process model across participants and related different interpretations to model users' experiences, priorities, assumptions, and views of a model as a mandate or guideline [6].

Research on science models has shown models' role in how students interpret phenomena (e.g., [37,38]). Further, students are more likely to assume and accept the accuracy of models rather than recognize where a model is reflective of reality and where it is not [39–41], suggesting that students do not seek to build a deeper understanding of the reality the model represents. Studies in science have also focused on what understandings students have after they engage with visual representations to guide development of learning tools and experiences that recognize students' interpretations of common representations (e.g., [7–9]). In the context of engineering design, we have a limited understanding of how students interpret the visual representations of existing design process models and, thus, cannot leverage this knowledge to guide how we support designers in choosing and using design process models. Given this limited research, we explored mechanical engineering students' perceptions of a single design process model in a prior study. We found consistent perceptions of the model—for example, the iterative nature of the model—as well as perceptions that varied, for example, relationships between different visual components [42]. In a follow-up study, we identified eight dimensions that students used to describe the usefulness of three process models and two features—iteration and level of detail—that students named as key distinguishing features across models [43].

Research Design

Our study investigated engineering student perceptions of design approaches recommended by three design process models. Our study aligns with the design research methodology framework as a "Descriptive Study I" [44], which is focused on description rather than prescription. In other words, our paper describes and comments on mechanical engineering students' perceptions of three design process model visualizations. However, we do not prescribe specific changes to any of the models. We aligned with Eckert and Stacey's [6] view that prescriptive process models should be evaluated based on their suitability for a particular purpose. Thus, the final decision on what, if any, updates should be made to the three process models investigated in our study is a case-by-case determination dependent on a particular model user's purpose for a model. We focused solely on the visual representations of design processes as they are more likely to be

Table 1 Participant characteristics

Demographic information	Participant characteristics (participant count)
Year of undergraduate education	3 (4); 4 (12); 5 (2)
Co-curricular experience	Co-ops or internships (12); project teams (15)
Age	20 (3); 21 (10); 22 (4); 23 (1)
Gender	Male (8); female or woman (10)
Race/ethnicity	Asian or Asian American (4); Guyanese (1); Hispanic or Latinx (2); Middle Eastern (1); Sephardic Jew: Middle Eastern, Hispanic (1); Caucasian or White (8); White/Asian (1)

Table 2 Process model presentation order by participant

Presentation order	Participants
123	P1, P6, P7
132	P9, P10, P13
213	P3, P5, P17
231	P2, P11, P14
312	P4, P12, P16
321	P8, P15, P18

Note: 1 = SED, 2 = EDP, and 3 = SPIRAL.

referenced by designers throughout design work. This approach allowed for a more controlled comparison of participant perceptions across multiple models.

Our study was guided by the following research questions:

(1) What recommendations for design process approaches and considerations do upper-level mechanical engineering students perceive to be present or absent in various design process models?
(2) How do student perceptions of recommendations vary by design process model?

In the theory of planned behavior, intentions are determined by one's attitude, perception of social pressure, and perception of ease of performing a particular behavior [45]. Behavior is predicted by intention and one's perception of ease of performing the behavior [45]. This theory implies that designers' claims about what a model suggests they do contribute to predicting their actual behaviors. Guided by the theory of planned behavior, we propose that design process models shape designers' intentions by influencing their attitudes about design, their conceptions of engineering design norms, and their perceptions of the ease of specific design behaviors [43].

Participants. Participants included 18 undergraduate mechanical engineering students recruited from a public Midwestern university. Our sample size is appropriate for a qualitative study focused on a nuanced understanding of participant perceptions and is consistent with the range of participants included in other qualitative design studies (e.g., [46,47]). We recruited students who had completed at least two courses of a three-course design and manufacturing sequence to (1) ensure their exposure to some design coursework and (2) reduce the number of factors influencing student perceptions. Recruitment involved sending emails to a university listserv for undergraduate mechanical engineering students and engineering student groups as well as a posting on a capstone course website. The emails and posting shared that we were interested in understanding students' views of design processes through interviews about a series of design process models and a link to a short screening survey that collected demographic and background information for those interested in participating. Participant characteristics are summarized in Table 1.

Data Collection. One researcher conducted a semi-structured interview with each participant about their perceptions of three different design process models. Prior research has shown sharing different visual displays and asking people to describe them to be useful in comparing the effectiveness of the visualizations [16]. Semi-structured interviews supported consistency across interviews in terms of the main questions covered while allowing the interviewer to ask follow-up questions to gain clarity and a fuller understanding of participants' perceptions [48]. All interviews were conducted via Zoom, audio-recorded, and automatically transcribed by Zoom.

The interview aimed to explore participant perceptions of different design process model visualizations. Participants were asked about their perceptions of three design process models: the Center for Socially Engaged Design's socially engaged design process model (referred to as SED) [49], Dieter and Schmidt's first three phases of an engineering design process (referred to as EDP) [50], and Ullman's spiral development of mechanical systems (referred to as SPIRAL) [51]. These models were selected because they all have prescriptive aspects, with SED including social and contextual dimensions in its visualization, and EDP and SPIRAL being commonly found in engineering design course textbooks for undergraduate students [52].

The interviews began by describing the study purpose and the interview format and acknowledging that no single design process model can capture everything a designer should do in every situation. Then, each model was presented individually, allowing participants to focus on one model at a time. Participants were given time to review and write notes about the model before answering questions about it. The order in which the three

Table 3 Interview protocol questions for data set

- What does this model recommend designers do when engaging in an engineering design process?
  - What recommendations are there for how designers do [repeat response]?
- What does this model recommend designers consider when engaging in an engineering design process?
  - What recommendations are there for how designers consider [repeat response]?
- What important aspects of engaging in an engineering design process do you think are not conveyed in this process model?
- What questions did you have about this model?

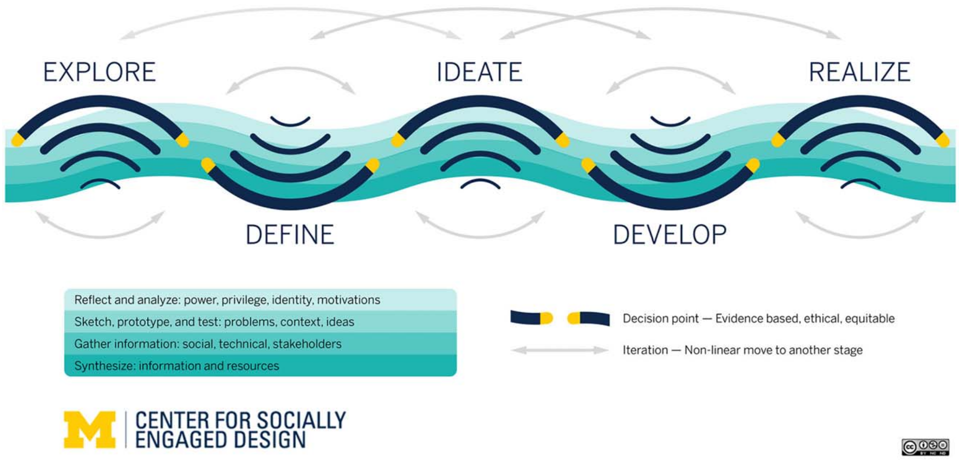

Fig. 1 Center for socially engaged design's process model [49] (colored version is what was used in this study). This model is referred to in this paper as the SED process model.

process models were presented was counterbalanced across the 18 participants, as shown in Table 2, to mitigate any order effects. Interviews concluded with participants viewing all three models together and answering comparison questions. Interviews lasted between 42 min and 72 min, and participants received compensation (gift cards of $20). This study includes the data from the portions of the semi-structured interviews when participants considered each model individually, which was approximately the first three-quarters of the interview. The interview protocol questions for this portion of the interviews are included in Table 3.

Participants were only shown visual representations of the process models, along with the model's name and citation in "Author, Year" format. No verbal or written descriptions of the models were provided to participants. The visual representations presented to participants are shown in Figs. 1–3.

Some participants had, at least potentially, seen some of the process models used in this study before. Thus, at the end of each interview, participants were asked about their familiarity with each of the three models. Participant familiarity is summarized in Table 4, with "Unsure" indicating that participants found the model familiar or similar to something they had seen before but were uncertain if it was the exact process model they had encountered previously.

Data Analysis. Our data analysis process drew from King's [53] overview of template analysis and Saldaña's [54] methods of theming data. In addition, our data analysis approach aligned with Walther et al.'s [55] recommendations for supporting validity. For example, we decided to use iterative analysis procedures to support theoretical validation, and we required explicit discussion of topics to support process reliability. Another example is we started with in vivo coding to support communicative validation.

First, we familiarized ourselves with the data by reviewing, correcting, and reformatting the transcripts generated by Zoom. We then used in vivo coding—using participants' own language as codes [54]—of two participant transcripts (P4 and P17) to generate an initial list of codes. These codes focused on the perceived presence and absence of recommendations for design. An initial codebook, akin to an initial template in template analysis [53], was developed by grouping together similarly coded data related to recommendations for engagement in design work, following a process similar to pattern coding [54]. We then used NVIVO [56], a qualitative data analysis software, to apply codes to interview transcripts from a larger subset of participants (P2, P4, P15, and P17). New codes were added to the codebook as additional recommendations were identified. The codebook was refined throughout the process of coding five additional transcripts. The finalized codebook remained constant for coding the remaining nine transcripts. Once all 18 transcripts had been coded, we conducted matrix coding queries in NVIVO to summarize participant counts by code and design process model.

In alignment with recommendations by Maxwell [57], we determined the appropriate unit of analysis for our research questions was the participant level, meaning that while some participants named the same characteristic from a model multiple times, we did not inflate the findings by counting the number of mentions, but rather counted the number of participants who reported the characteristic. This focus on the individual as the unit of analysis has also been leveraged in other design scholarship (e.g., [47,58]).

Guided by our research questions, we analyzed participant counts to identify the most salient patterns of discussed recommendations. Our findings focus on codes with relatively high participant counts and those that demonstrated variation across the three models or within a theme. Presenting our findings by using the themes as the main structure follows one of the approaches suggested for template analysis [53]. We further modified code names to explicitly connect participants' discussions with the text included in the visualizations. The refinement of code names and code descriptions ensured alignment with coded participant excerpts.

Procedural validation [55] was supported by regular meetings between the first author—the main coder—and the second author. At the time of analysis, the first author was a graduate mechanical engineering researcher with prior professorial experience as a product development engineer and training in qualitative methods, while the second author is an experienced qualitative researcher

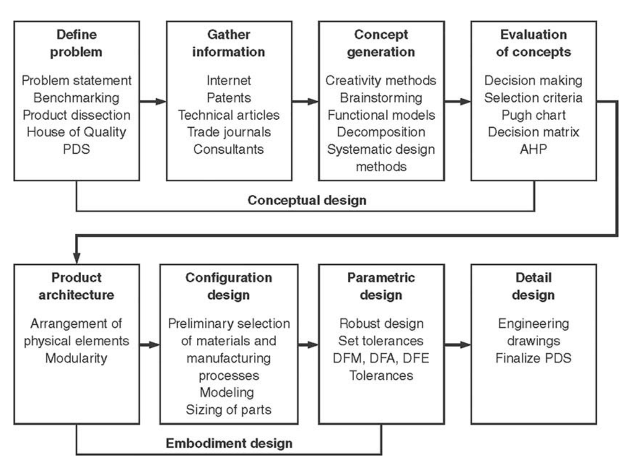

Fig. 2 Dieter and Schmidt's first three phases of an engineering design process [50]. This model is referred to in this paper as the EDP process model.

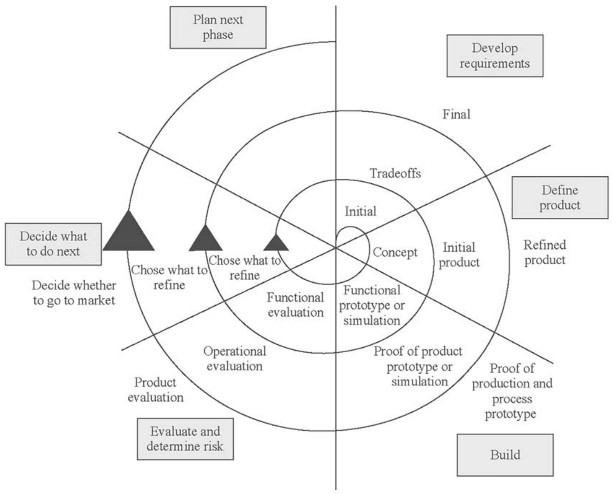

Fig. 3 Ullman's spiral development of mechanical systems [51]. This model is referred to in this paper as the SPIRAL process model.

and design researcher. Both authors have a close relationship with one of the process models under investigation and have taught undergraduate engineering students other process models not under investigation in this study. Given our positionalities, we paid particular attention to representing participants' views of the models rather than our own. Consistency in our analysis was maintained by requiring explicit participant discussions of those topics represented by our codes. Double coding, or applying multiple codes to the same excerpt, was allowed unless otherwise noted in the findings. Our findings reflect participants' perceptions related to the three models and are limited to those perceptions that participants expressed during the interviews. In the following findings section, terms such as "perceived," "noticed," "described," and "discussed" indicate perceptions conveyed by participants in their interviews. Pragmatic validation [55] is achieved by the transparency of data, including descriptions that allow readers to consider the transferability of the findings to other contexts.

Table 4 Participant familiarity with process models

Cite	Process model	Yes	Unsure	No
[49]	SED	4	1	13
[50]	EDP	0	5	13
[51]	SPIRAL	0	3	15

Findings

Participants' perceptions of the three design process models were categorized into five areas of design work: (1) starting and moving

Table 5 Participants counts for each area of design work by process model (out of 18 total participants)

Area of design work		Process model: SPIRAL	SED	EDP
Starting and moving through a design process	Recommended way to start a design process			
	Explore/start with exploring	0	7	0
	Define problem/start with problem	1	1	10
	Develop requirements/start with requirements	9	0	0
	Presence and approach to iteration			
	Flexible iteration present[a]	0	14	0
	Feedback iteration present[a]	16	6	0
	Feedback iteration absent	3	0	16
Gathering information	Presence of gathering information as a general action			
	Gather information in general present	0	10	5
	Gather information in general absent	1	0	2
	Presence of gathering information from X			
	Multiple sources present	0	3	9
	Domain experts present[b]	0	0	3
	Stakeholders present[b]	1	7	1
	Stakeholders absent	6	1	4
Prototyping	Presence of prototyping			
	Prototyping present	13	6	3
	Prototyping absent	0	0	1
Evaluating or testing	Presence of evaluating or testing			
	Evaluating or testing present	16	2	3
	Evaluating or testing absent	1	6	8
Aspects of focus in a design process	Presence of economic aspects			
	Economic aspects present	7	0	2
	Economic aspects absent	0	3	6
	Presence of environmental aspects			
	Environmental aspects present	0	1	0
	Environmental aspects absent	2	1	5
	Presence of social aspects			
	Social aspects Present	0	15	1
	Social aspects Absent	6	1	9
	Presence of technical aspects			
	Technical aspects present	7	3	11
	Technical aspects absent	1	8	4

[a]Flexible iteration was not double coded with feedback iteration.
[b]Domain experts was not double coded with stakeholders.

through a design process, (2) gathering information, (3) prototyping, (4) evaluating or testing, and (5) aspects of focus in a design process. The following subsections discuss participant perceptions of model recommendations across these five areas and, at times, contrast their perceptions of model recommendations with their perceptions of what is absent from the model—including both what is missing (i.e., should be included) and what is simply not present (i.e., not a judgment on if it should be included or not). A summary of participant counts of perceived recommendations is provided in Table 5.

Perceptions of Design Process Model Recommendations for Starting and Moving Through a Design Process. Participants noted recommendations they perceived from the models about how one gets started and moves through a design process, including recommendations on first steps in design and approaches to iteration within a design process.

Participants discussed different approaches to starting a design process based on the three models. In some cases, participants noted the labels within the models as emphasizing a place to start design work. Seven participants perceived they should start design by exploring based on SED, 10 participants perceived starting with a problem based on EDP, and nine participants perceived they should start with requirements based on SPIRAL. In contrast to the specific language in the model, one participant perceived SPIRAL to recommend starting with a problem and one participant perceived SED to recommend starting with a problem. Interview excerpts that serve as examples of how participants perceived ways to start design work are presented in Table 6.

Some participants perceived that EDP and SPIRAL were missing early steps of the design process. For example, gathering information should precede defining the problem, or defining the problem should come before creating an initial design. In addition, some participants highlighted that SPIRAL did not indicate the need for a provided problem definition in order to start with developing requirements. Interview excerpts that provide further elaboration on these ideas are provided in Table 7.

Participants not only discussed the recommended starting points for design but also perceived recommendations for progressing through design, particularly regarding the presence or absence of iteration. They discussed two types of iteration. The first type, referred to as "feedback iteration," involved going back to a previous point in the design process, i.e., it acted as a feedback loop. The second type, termed "flexible iteration" in line with our previous research [42], involved non-linear movement, including back-and-forth transitions between stages of a design process. While SED includes the language "Iteration—Non-linear move to another stage," participants perceived both feedback and flexible iteration in this model. Among our participants, SED was the only one perceived to recommend flexible iteration ($N = 14$). Sixteen participants perceived SPIRAL to recommend feedback iteration, while six participants perceived SED to recommend feedback iteration. No participants mentioned EDP as recommending either kind of iteration. Instances where participants mentioned the term "iteration" without providing specific details were included in the counts for feedback iteration. In addition, although flexible iteration encompasses feedback iteration, instances of flexible iteration were not double coded with feedback iteration in order to highlight differences in participant counts.

Participants also provided critiques of certain process models, expressing that iteration was missing as the process model did not include a recommendation for a designer to revisit previous stages in the design process. Most of the participants ($N = 16$) perceived EDP to be missing iteration, and a few participants ($N = 3$) felt the same about SPIRAL. Interview excerpts that serve as examples of how participants perceived iteration are presented in Table 8. Additionally, some participants described EDP as requiring thoroughness or doing the best with the one chance at each design stage; example interview excerpts are included in Table 9.

Perceptions of Design Process Model Recommendations for Gathering Information. Participants discussed the recommendations of the process models regarding gathering information, including sources of information. Some participants perceived SED ($N = 10$) and the EDP process model ($N = 5$) as recommending information gathering information or conducting research but not the sources or methods from which information could be gathered. Although SED and EDP include "Gather information," a few

Table 6 Participant interview excerpts illustrating perceptions of recommended ways to start a design process

Recommended way to start a design process	Interview excerpt
Start with exploring	• This model recommends that engineers become educated on whatever thing they're working to maybe address before they even decide that it's a problem. So, getting educated and exploring [is] happening before you define the problem. (P17, SED)
Start with problem	• The way [the model] suggests you do the design is: you start with defining a problem and then research about it, to ensure that you have all the- you know all the terminology, you know sort of what's out there about this problem and collecting all that information. (P13, EDP)
Start with requirements	• It doesn't start with the problem definition; it starts with developing requirements. So, it goes straight into the engineering requirements… And then, iterating on the product, rather than starting with understanding the problem and then developing requirements from the problem. (P2, SPIRAL)

Table 7 Participant interview excerpts illustrating additional ideas about how to start a design process

Interview excerpt
• Gather information should have been before defining the problem. Or, I guess, on both sides of it. Because if you're given a problem… you would have to do your own research on that and figure out that information before you're actually defining the problem. And then figuring out if the problem you were given is the actual problem that you're trying to solve. (P9, EDP)
• Most of the steps that I think are missing come before Initial. I don't think this model really touches on how you actually get to your initial design. And I learned these things [how you get to an initial design]… Before coming up with a design, first coming up with a problem definition and evaluating your stakeholders, setting your requirements, gauging potential interest in a product. (P16, SPIRAL)
• This focuses a lot more on a project with a defined engineering problem… you start by developing requirements, but you don't necessarily start by defining a problem, so there isn't a lot of talk about how you define the scope of your problem, or engaging stakeholders, or take all of that, social context, environmental context, into account. So that stuff would have to be provided for you, for this project to follow this design cycle. (P13, SPIRAL)

Table 8 Participant interview excerpts illustrating perceptions of the presence and approach to iteration

Presence and approach to iteration	Interview excerpt
Flexible iteration present	• I think broadly the five steps "Explore," "Define," so on and so forth, I think that's the overall structure, but the arrows, like Iteration, indicates that you'll have to move back and forth at certain points. So, broadly for the whole process you're trying to get from exploring ideas to realizing an idea, but throughout that process it's… like it says "Non-linear," you may have to repeat stages or go back or skip or however it's applicable to what you're working on. (P10, SED)
Feedback iteration present	• The first thing that really stood out to me was this cyclical-ness of the model… It's telling them that your design process is going to be cyclical, you're always going to be coming back to similar steps of the process. And so, you know you're always going to be having a step where you're building something new [Build]. The next step being analyzing and determining risk [Evaluate and determine risk]. So, I think it effectively captures the cyclical nature of the design process. So, it's reminding engineers that it's an iterative process. (P16, SPIRAL)
Feedback iteration absent	• [An important aspect of engaging in an engineering design process that this process model is missing is] definitely the ability to go back and update things as needed. I know sometimes the design problem can change as you get more information… because you're always going to get more information, then there's not really a room to be able to go back and adjust things as needed. And then I think having the ability to go back and change certain aspects would make the overall process a lot easier, I think so you're not set on something. (P11, EDP)

participants ($N=2$ for EDP and $N=1$ for SPIRAL) noted instances where they felt the process model was missing information gathering. Table 10 provides interview excerpts illustrating participants' perceptions of general information gathering recommendations.

Participants also identified specific features of information gathering, particularly regarding information sources, and noticed a lack of recommendations for gathering information from stakeholders in the process models. Some participants perceived EDP ($N=9$) and SED ($N=3$) as encouraging information gathering from multiple sources. For EDP, participants often referred to the text within the "Gather information" box in the model, while for SED, participants pointed to the text after the "Gather information" undercurrent in the model. EDP contains "consultants," and three participants described it as recommending gathering information from consultants or engineering professionals. No participants mentioned these domain experts specifically when discussing the recommendations that they perceived from SED and SPIRAL. While SED includes the language of "stakeholders," all three models prompted at least one participant to describe gathering information from stakeholders ($N=7$ for SED, $N=1$ for SPIRAL, and $N=1$ for EDP), including people that will be affected by a design, end-users, customers, outside parties, and communities. Some participants also perceived a lack of recommendations for gathering information from people, either throughout the process or in specific parts, in

Table 9 Participant interview excerpts illustrating participants' perceptions of the need for thoroughness or making the most of one chance

The EDP…	Interview excerpt
Requires thoroughness	• [The model] recommends starting with a really clear problem statement. Obviously, it doesn't allow you to go back to the problem statement, so the first time around, you have to be really thorough about "Benchmarking," looking at other solutions [Product dissection], keeping quality in mind [House of Quality]… (P4, EDP) • It definitely recommends a really linear approach and I would say thoroughly completing every block before moving on to the next. (P4, EDP) • It definitely- it recommends thoroughness and a lot of clarity before kind of moving on to the next step. It's almost like a to do list for each part that you have to get done in order to move on to the next step. So, there's definitely a thoroughness to that, I would say. (P7, EDP)
Requires doing the best with one chance	• Since the arrows only go in one direction, it makes me- if I were following this design process as it's shown to me, I would not feel inclined to go back stages. I would feel inclined to try to do the stage as best as I can, and then move on to the next stage. (P2, EDP) • This one seems like you have one chance, so you better use the best option, like that's kind of the rigidity of it is like that's why you would use a Pugh Chart because you would try it- you would test all your options with a Pugh Chart before even designing it because you're not gonna be able to go back and forth and try different things yeah. (P7, EDP) • I think it really wants you to solidify certain aspects of it before moving on to like the next component… So, under "Product architecture," it seems once you have that there's not really space to go back and change things… so I think there's a strong focus on being sure of the design before you look at additional components to it. (P11, EDP)

Table 10 Participant interview excerpts illustrating perceived presence of gathering information as a general action

Presence of gathering information as a general action	Interview excerpt
Gather information in general present	• [The model] recommendations to do your research and make sure that you begin with your problem statements so that you know what you're researching and what it is that you're looking for which I think is a really, really important part of the design process is your initial research and kind of the things that you've- you find are already in existence for whatever problem you're trying to solve. (P3, EDP) • I think at each step it really focuses on gathering as much information as you can about not only the product itself, but also the impact it could have. So, I think that's being evaluated at each step. (P11, SED)
Gather information in general absent	• [The model] doesn't talk about information gathering… it doesn't have anything about gathering information. (P2, SPIRAL)

Table 11 Participant interview excerpts illustrating perceived presence of gathering information from X

Presence of gathering information from X	Interview excerpt
Multiple sources present	• In the gather information step it says, you know, social, technical, then stakeholders (P15, SED) • In gathering information, it mentions all the different types of information that you can gather with "Internet, Patents, Technical articles" or journal articles, so it just gives you all the dimensions necessary to make sure you don't skip a step. (P13, EDP)
Domain experts present	• I feel like it recommends designers consulting other engineering professionals to bolster their technical knowledge that they may want to improve or something in regards to the configuration design or parametric design. (P17, EDP)
Stakeholders present	• Now that they've proved that the functionality of the product [and are in the second go around the spiral], now they're sort of proving the other facets of their product in the "Proof of product prototype or simulation." I don't really know what that entails but… maybe this is getting… potential customer feedback. (P16, SPIRAL) • When it talks about gathering information it really like it starts off with like "social" so it really wants to make sure that in the design process you're interacting with people and getting their feedback, so it recommends that they consider talking to like a lot of people and gathering as much as they can. (P8, SED) • Gathering information from the internet or patents, technical articles, talking to other people, or looking into journals. (P8, EDP)
Stakeholders absent	• [An important aspect of engaging in an engineering design process that this process model is missing is] stakeholder engagement, or just… I mean this could be kind of one person doing an entire design process themselves so… it's kind of- like the- well the validation and verification phase where you'd be interacting with stakeholders, or making sure you're designing the right product, and all those types of things, seem to be missing a bit. (P4, SPIRAL)

Table 12 Participant interview excerpts illustrating perceived presence of prototyping

Presence of prototyping	Interview excerpt
Prototyping present	• I think it focuses a lot on building different versions and iterations of the model, because it shows almost three- three phases of prototype and simulation at three different parts and also constant evaluation of those three prototypes… I think this one's based more on designing the model, developing a prototype, and then evaluating the functionality of that prototype and more on the hands-on learning compared to literature reviews and taking inspiration from existing knowledge resources since that that's not explicitly mentioned in this. (P5, SPIRAL)
Prototyping absent	• I think prototyping is missing, I mean I feel like maybe that would be after engineering drawings, maybe this is just ending- I mean it's obviously ending before the product is built, because you just have a drawing at the end, but… feel like some sort of prototyping could be included. (P4, EDP)

SPIRAL ($N = 6$), EDP ($N = 4$), and SED ($N = 1$). Table 11 presents interview excerpts exemplifying participants' discussions on the presence or absence of information gathering source recommendations in the process models.

Perceptions of Design Process Model Recommendations for Prototyping. Participants discussed the inclusion or absence of recommendations for prototyping in the process models. While SED and SPIRAL include the word "prototype" at least once, participants had varying perceptions of the recommendations for prototyping across the process models. Some participants perceived a recommendation for prototyping in SPIRAL ($N = 13$), SED ($N = 6$), and EDP ($N = 3$). Only one participant perceived a lack of prototyping, which they noted in response to EDP. Interview excerpts that serve as examples of how participants discussed prototyping are shown in Table 12.

Perceptions of Design Process Model Recommendations for Evaluating or Testing. Some participants perceived recommendations regarding the evaluation or testing of designs, prototypes, products, materialized concepts, or simulations (SPIRAL $N = 16$, EDP $N = 3$, and SED $N = 2$). However, several participants felt the models did not provide recommendations for evaluating or testing (EDP $N = 8$, SED $N = 6$, and SPIRAL $N = 1$). Here, we captured participants' attention to evaluating developed "designs" that were materialized, simulated, or prototyped (which could include prototypes of processes). Interview excerpts that serve as examples of how participants perceived evaluating and testing are shown in Table 13.

Perceptions of Design Process Model Recommendations for Aspects of Focus in a Design Process. Participants discussed multiple considerations as present or absent in the three process models. The salient aspects identified were economic, environmental, social, and technical. Some participants perceived SPIRAL ($N = 7$) and EDP ($N = 2$) recommendations for consideration of economic aspects, while no such recommendations were attributed to SED. Relatedly, some participants perceived an absence of considerations of economic aspects from EDP ($N = 6$) and SED ($N = 3$). Only SED ($N = 1$) was perceived by participants to include a recommendation for consideration of environmental aspects, while some participants perceived EDP ($N = 5$), SPIRAL ($N = 2$), and SED ($N = 1$) to lack such recommendations. Some participants perceived SED ($N = 15$) and EDP ($N = 1$) to recommend consideration of social aspects, but no participant perceived SPIRAL to recommend it. Some participants described the absence of recommendations for consideration of social aspects (EDP $N = 9$, SPIRAL $N = 6$, and SED $N = 1$). EDP ($N = 11$), SPIRAL ($N = 7$), and SED ($N = 3$) were perceived by some participants to recommend consideration of technical aspects, while participants noted the absence of such recommendations in SED ($N = 8$), EDP ($N = 4$), and SPIRAL ($N = 1$). Table 14 provides interview excerpts exemplifying participants' perceptions of these four aspects.

Discussion

The findings revealed what stood out to participants about how to engage in a design process based on three different process models. We did not ask participants if specific elements were present or not in the models, but rather open-ended questions about what the models recommended and what important aspects of design

Table 13 Participant interview excerpts illustrating perceptions of the presence of evaluating or testing

Presence of evaluating or testing	Interview excerpt
Evaluating or testing present	• There's frequent evaluation of the design. So certain flaws in a design can be caught earlier on and updates can be made as needed, as well with the sort of round process. (P11, SPIRAL) • I think this [SPIRAL] model tells designers to consider constant- to constantly evaluate your product and constantly evaluate your prototype. One big part of it is doing tradeoffs between your proof of product prototype and also evaluation… the spiral motions [are] telling you to not create one design and then you're done with it, you're constantly adding on improvements and building upon your ideas from the beginning. You have a concept, you make a prototype, but you're not done then. You have to evaluate and then once you evaluate then you decide what should I add, what should I improve or improvise based on this prototype and concept. (P12, SPIRAL) • Another thing is it's a lot about… Sketch, prototype, so it's just about… fabricating your ideas to more physical… it always implores you sketch it [an idea] out or model it and prototype it so that there is a physical manifestation of it which always makes it easier for (1) other people to understand what your concepts are and (2) it also helps you see what the weak points of that concept could be because let's say design some mechanism, like it's in your mind, and certain parts of it will be blurry for you and once you put it on paper, create some type of prototype in electronic form, you start to see "Oh wait, how was this going to fit there." Stuff like that. (P13, SED)
Evaluating or testing absent	• There's not really like a testing component, I would say it's missing. It's just sort of like a finalized design, it says like pick your part for your design, pick your manufacturing process, set tolerances, and then put the product out, is kind of how I see it. It doesn't have any parts about like maybe testing and coming back to gather more information. (P7, EDP) • I think in the "Evaluate & select concept" box, there's really no like "test your design" or- I don't know, I feel like it kind of forgot to include like the whole testing and analyzing stage in the design process, as well. It doesn't- when it's saying evaluate, it's more like evaluate the- your different ideas for the concept, rather than like evaluating the performance of your concept. (P15, EDP)

engagement were not conveyed by the models. This approach then allowed us to identify salient participant perceptions related to engagement in an engineering design process. Participant perceptions varied across models as well as within models. Also relevant from our findings is what areas of design work many participants did not comment on. We discuss these findings in the following sections.

Variation in Participant Perceptions Across Models. Our findings revealed several patterns that suggest different design process models make perceptions of certain recommendations more salient than others. For example, the types of iteration most frequently noticed by participants varied by the process model they were considering. Participants described two main types of iteration in our study: feedback iteration, where they could return to a previous stage, and flexible iteration, allowing unrestricted movement between stages. Sixteen participants named an absence of iteration in EDP, 16 participants noted feedback iteration as recommended in SPIRAL, and 14 participants identified flexible iteration as recommended in SED. This lack of iteration or type of iteration pursued in a design process has implications for design outcomes. Iteration is recognized as a fundamental aspect of design [59] and is commonly observed in real-world projects [60]. However, research suggests that beginning designers navigate design processes haphazardly or follow linear approaches [26]. Combining this scholarship with our findings suggests that scaffolded representations of iteration that progressively enable more complex movement—such as the absence of iteration in EDP, feedback iteration in SPIRAL, and flexible iteration in the SED process model—could benefit beginning designers.

Most participants perceived SPIRAL to recommend prototyping, but fewer perceived prototyping recommendations in SED, and none reported recommendations in EDP. How models direct designers to prototype is important; recent design literature recognizes prototyping as a continuous tool or activity throughout the design process rather than a single stage [61–63], yet novice designers often view prototypes as trial builds of final products or for testing functionality, with less common understandings focused on communication, feedback gathering, and decision support [63]. As the uses of prototypes are broad, including enabling communication, informing decision-making, and aiding learning [61,63], models that limit designers' recognition of their uses may cause this tool to be underleveraged to support design success.

The variations we observed in participant perceptions across process models align with our prior work, where participants used dimensions of usefulness, along with iteration and detail level, to distinguish the three different process models [43]. Variation across the models reflects their nature as abstractions, which inherently limits the information they convey [6]. Thus, trade-offs are inevitable when determining what to include in a particular process model. Another example was that participant perceptions of how to start a design process varied, including exploring, starting with the problem, or starting with requirements. Exploring involves divergent thinking, searching for and generating multiple alternatives [64]. Defining the problem focuses on convergent action, describing the end goal [64,65], without emphasizing the importance of exploring potential design problems. Starting with requirements also involves convergent action, listing criteria for a successful solution [50,51]. Crismond and Adams' [26] scholarship of integration study highlighted that beginning designers treat problems as well-structured and prematurely jump to solution generation, while more informed designers delay decision-making to explore and iteratively frame the problem. Of course, how one begins a design process is dependent on the design context such that, at times, beginning with convergent actions will be appropriate, while at other times beginning with divergent actions will be better suited. The segmentation of perspectives across these three process models on how to begin a design process suggests that novice designers' awareness of these different approaches is something that could be facilitated by leveraging multiple process models.

Following the theory of planned behavior [45], participants' perceptions of recommendations (e.g., regarding iteration, prototyping, and starting a process) can influence their intentions and, ultimately, their engagement in design work. Thus, our findings suggest that participants would pursue distinct design paths based on the model or models they rely on to guide their work.

Variation in Participant Perceptions Within Models. In addition to perceiving different models differently, participant perceptions varied for a single model. For example, three participants perceived EDP to recommend evaluating and testing designs. In comparison, eight participants perceived an absence of recommendations to evaluate and test in EDP. This variety of perceptions for a single process model aligns with prior research showing that engineers can interpret the same model differently [6,42], even when

Table 14 Description of aspects of focus and participant interview excerpts illustrating perceptions of recommendations for each aspect of focus

Aspect of focus descriptions	Interview excerpt
Economic: financial considerations, including the feasibility of making money, profitability, costs associated with a product, and references to the "market" without additional elaboration.	• The decide whether to go to market seems very economical and capitalistic as an engineering system where we're engineering things for companies and to make money and not necessarily for the betterment of society for all people, right. So that, in my mind implies a limitation where if it's not economical we shouldn't- the decision is that if it's not economical, it won't make money on the market and we shouldn't produce it. Whereas it may not be economical, but it may just be advantageous for society and disadvantaged communities around the globe. (P17, SPIRAL, noting a presence of economic aspects) • I think, at least what I learned in my classes was your design should also be like influenced by the feasibility of its production, as well as, you know, the feasibility of actually making money. You're not going to design something that's not going to make you money. So that that's sort of not addressed here. (P16, EDP, noting an absence of economic aspects)
Environmental: considerations of impacts on nature of a product anytime during its lifecycle.	• [This model] implores, at every step it implores you look at again- at what kind of you know societal context, environmental context, and maybe or, you know, the power dynamics and stuff that are in play, so it always implores the designers at each step to sort of take into account the context in which their designing it, so that you don't harm a community or you always keep sort of the primary stakeholders who are going to be affected by this project in mind, or product in mind. (P13, SED, noting a presence of environmental aspects) • It kind of stops just at engineering drawings. And I think there is like part of the process that's- that's worthy of considering after that… considering things like life cycle: how are you going to like retire the design. (P10, EDP, noting an absence of environmental aspects)
Social: considerations of society and impacts on people, communities, stakeholders, and customers.	• I like how there's decision points at the transition between each stage or ideally also between any iterative stages moving back and forth, that's a decision as well. I really liked how these decision points are focused on being ethical and equitable, they shift the focus away from the engineers making efficiency or monetary decisions and more to a human centered design approach. (P17, SED, noting a presence of social aspects) • And also, what I said earlier about like the fact that it's really technical, I think, like the other one it needs other aspects or it needs [to] at least suggest that you need to take into consideration aspects besides technical, like social or environmental. (P2, SPIRAL, noting an absence of social aspects)
Technical: considerations of physical and scientific functioning, manufacturing, and production.	• I think it considers a lot of just the scope of what you're trying to do. So, meaning it considers a lot of the manufacturing methods of constructing a product and a lot of the raw materials that are needed. So, making sure that your sizing, your dimensions are correct, and everything technical. (P14, EDP, noting a presence of technical aspects) • It's not nearly as technical, which I don't think is an issue… technical in the regards that it doesn't go into details about the specific technical parameters that would need to be done at each step. (P14, SED, noting an absence of technical aspects)

those same engineers assume there is only one "sensible interpretation" [6]. Furthermore, we found this variation in participant perceptions of the same process model when all participants were from the same university and had taken some of the same design coursework, emphasizing that a process model will not be universally interpreted in the same way by all model users.

Noticeable Omissions From Participant Discussions. Our findings highlight several areas of design work where, regardless of the process model, many participants did not comment on a particular area of design work. For example, many participants did not perceive recommendations for information gathering from domain experts and stakeholders across the three models. Gathering diverse perspectives, including from across stakeholders and domain experts, can improve designers' ability to adequately address a range of needs and maximize impact [66–70]. However, prior research has shown that beginning students gather less information and less varied information than more advanced students [71] and that novice teams prioritized domain expert perspectives [66]. The lack of design process models to encourage attention to diverse stakeholders and domain experts throughout design could allow these behaviors to perpetuate and support the false conception that engineering design does not require stakeholder engagement.

The presence or absence of environmental aspects was rarely discussed in any of the three models. Other important considerations were discussed relatively more frequently by participants across the three process models; however, each process model highlighted a certain aspect more than others. Participants most frequently noted consideration of economic aspects in SPIRAL, consideration of social aspects in SED, and consideration of technical aspects in EDP. The lack of explicit attention to certain aspects in a single model or collection of models may have varying impacts depending on the disciplinary norms. Engineering has historically been presented as a purely technical discipline [72], with emphasis on technical analysis [73], technical decisions [74], technicist identities [75], and cost considerations [50,51,76], while social aspects have received less attention. Calls for engineering education to develop students' social and technical expertise persist [77,78], as engineers face challenges attending to social aspects [79] and students lose interest in attending to social aspects [80]. Relatedly, engineering education that integrates technical aspects with sustainability (economic, environmental, and social aspects) has some support [81], although sustainability within engineering often prioritizes economic and environmental aspects over social aspects [82,83]. Explicit representation of environmental and social aspects in design process models may be a tool for shifting engineering design behaviors to attend to these aspects.

Limitations. One limitation is that participants only had access to visual representations of the process models. This choice ensured consistency in the information and focus on key information, following the principle of salience for visual displays [16–19], but did not allow supplementary text or verbal explanations to support students' deeper understanding of the models. Further, while each of the process models had words within their visual representation, this study did not focus on the specific choices of what words were included but rather on participant perceptions of each model as a whole.

People's perceptions of design process models may be affected by many factors apart from the information contained in the models' visualizations, for example, their thoughts about and previous experiences with design. Our sample had zero non-binary people, consisted entirely of folks in their early twenties, and most (13/18) participants identified as White, Asian, or both. A more diverse sample of participants may have shifted which perceptions of recommendations were most salient. Additionally, participants had limited time to review the models, and their perceptions may have been different with more time or design practice with the models. Lastly, due to word count limitations, we focused on salient patterns and could not include all participant perceptions across the models.

Implications. Model users—especially educators—can use our findings to guide the development of engineering design education and training. Our findings highlight several areas of design work that many participants did not comment on, regardless of the design process model they were reviewing. For example, the noticeable omissions we observed included discussions of gathering information from a diverse set of stakeholders and discussions of environmental aspects. These omissions suggest a need for further development of engineering design pedagogy to emphasize the importance of attention to social and environmental aspects.

Design educators can also use our findings to guide how they teach when using any of the three process models explored in this study as they are. For example, relatively few students discussed prototyping when reviewing the SED process model even though the word "prototype" appears in the visual representation of that model. Instructors who choose to use the SED process model could have students develop prototypes at each stage of their process as a way of highlighting the undercurrent of the SED process model.

In addition, our findings can inform updates to the models by their creators or users based on the specific use purpose. While we do not suggest specific updates to any of the models, our findings do support informed iterative development where there is misalignment for model creators, instructors, students, and design practitioners by providing empirical evidence of ways in which the three process models are currently perceived by 18 mechanical engineering students.

Our research reinforces the importance of using multiple design process models for instruction and training, especially for novice designers. In this study, different participants perceived the same process models in different ways. Our findings aligned with prior research that found engineering and project managers had diverse interpretations of the same process model [6]. Thus, different models are needed to communicate the same concept to different people.

Multiple process models are also important for an individual model user. We found that not everything present in the visual representation was translated into meaning for our participants, but certain visual representations were more likely to translate certain meanings. Following the theory of planned behavior [45], which connects individuals' perceptions to their engagement in design work, model users can draw on knowledge of which visual representations are more likely to translate to certain meanings to purposely select model(s) that will support particular kinds of engagement. For example, model users who aim to promote a holistic design practice may strategically select a collection of models that will likely highlight a range of considerations.

Conclusion

In our study, we examined mechanical engineering students' perceptions of three design process models: the Center for Socially Engaged Design's socially engaged design process model [49], Dieter and Schmidt's engineering design process model [50], and Ullman's spiral development model [51]. We focused on participant perceptions of recommendations for design approaches and considerations. Participant perceptions varied across the three process models and varied for a single process model. Thus, while certain process models make some recommendations for design work salient to model users more frequently, we cannot expect a process model to be universally perceived one way. Variation in perceptions across design process models included initiating and progressing through design work, gathering information, prototyping, evaluating or testing, and aspects of focus. Furthermore, our findings highlight several areas of design work that many participants did not discuss. These findings can inform the development of design pedagogy, guide the use and refinement of models, and support the value of using multiple design process models in engineering education and practice.

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Conflict of Interest

Kelley E. Dugan and Shanna R. Daly are both affiliated with the Center for Socially Engaged Design. Dugan worked as a facilitator at the Center for Socially Engaged Design for several years while completing their Ph.D., while Daly is a co-founder of the center, current director of research and evaluation, and part of the team that developed the socially engaged design process model investigated in this study.

Data Availability Statement

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

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