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INVESTIGATION OF MECHANICAL ENGINEERING STUDENTS' PERCEPTIONS OF DESIGN PROCESS MODELS

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ABSTRACT

Engineering designers, who are increasingly tasked with solving complex problems, leverage various forms of support to practice and develop their design skills as well as ultimately navigate the complexity of the problems with which they are faced. Design process models are one such form of support, particularly those process models that prescribe how to design. To better understand how process models impact design approaches, this preliminary study analyzed semi-structured interviews—focused on participants' perceptions of three design process models—with six upper-level mechanical engineering students. Across participants' responses, we identified eight dimensions used to distinguish the usefulness of each process model: impacts considered, project scope, stakeholder interactions, problem definition, project deliverable, solution novelty, solution type, and process applicability. In addition, participants differentiated the three process models based on iteration and the level of detail within a model. Our findings highlight the importance of accounting for varying interpretations across process model users and suggest that students would benefit from multiple design process models, including process models that recognize society and people in engineering decision-making.

Keywords: design process, design theory, design representation, design visualization, education

1. INTRODUCTION

Engineering designers are increasingly tasked with solving complex problems where they must attend to the interests of multiple stakeholders, account for environmental impacts, and more, in addition to the functionality of a generated solution. To navigate this complexity, engineering students and practitioners leverage scaffolded tools, training, and support to practice and develop the design skills necessary to create successful solutions.

One area of relevant support is design process models, particularly those that generally define how to design, i.e., have prescriptive characteristics [1]. Prescriptive process models are one mechanism for guiding design and problem-solving activities throughout a project [2]. For example, the W-model design process prescribes progression through five phases: define, ideate, synthesize, assess, and reflect [3]. Archer [4] proposed systematic approaches as particularly useful for designers in several situations, including when addressing complex problems and when there is a high probability of being wrong. Descriptive design process models can also support designers' understanding of design processes by conveying how design occurs in practice. For example, a model that connects problem and solution in a loop [5, p. 27] describes the co-evolution of problem-solution [6], i.e., "information needed to understand the problem depends upon one's ideas for solving it" [7, p. 161]. While we are pragmatically leveraging the classification of process models as descriptive or prescriptive to highlight the ways in which different aspects of process models can support designers, it is important to highlight that much of the literature on design process models contains both descriptive and prescriptive aspects [8] and a single design process model can be both descriptive and prescriptive [1], [9].

Few studies have explored how process models impact design approaches. In guiding designers' actions, the prescriptive traits of design process models are by definition aimed at shaping behavior. Thus, we are focused on the prescriptive aspects of design process models. In addition, we

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recognized a lack of attention to social and contextual considerations in many design process model visualizations. We intentionally chose to investigate more traditional design process models and one process model intending to emphasize social engagement to see if/how perceptions differed.

This study aimed to investigate students' perceptions of design process models. We focused on students because design process models are one tool for teaching students how to design [10]. In addition, students have the least amount of experience and therefore have a high probability of being wrong—meaning they would benefit from a systematic approach [4]. We focused on perceptions of process models because understanding these perceptions is a critical step in understanding the impacts design process models can have on students' design practice, as how "designers understand - implicitly, explicitly, and tacitly - what it means to design has an impact on how they will approach a design task" [11, p. 129]. This premise is supported by the theory of planned behavior, which describes that intentions to perform particular behaviors can be predicted from attitudes towards a particular behavior, perceived social pressure to (not) perform the behavior, and perceived (ease) difficulty of performing the behavior; and that intentions, combined with perceived (ease) difficulty, are predictive of actual behavior [12]. As a tool for engineering training and education, we posit that design process models can shape intentions—and therefore, behavior—by informing students' attitudes, reflecting/shaping engineering culture, and affecting what students practice/barriers to practice. Our position aligns with the theory of planned behaviors' postulation that behavior is a function of beliefs [12]. Furthermore, this work is motivated by the consensus that design outcomes are impacted by the training and experiences of the designer(s) [1].

2. BACKGROUND

2.1 Prescriptive Design Process Models

Prescriptive design process models define what a process should be [1] and are intended to be used in practice [13]. Gericke and Blessing [10] highlighted that researchers are motivated to develop prescriptive design process models to support communication during design, reduce the likelihood of forgetting an important step or consideration while designing, and facilitate design education. Finger and Dixon [1] pointed out that an often implicit assumption of research on prescriptive design process models is that designers could improve design outcomes by following the prescribed process. However, no research (up to that point) had verified that [1]. More recently, researchers have acknowledged that there is little (if any) research that verifies that following prescriptive design principles leads to better design outcomes [14].

However, a few recent studies support the idea that leveraging prescriptive design process models correlates to quality design outcomes, as measured by in-class demonstrations [15], and is associated with improving student design practices [3]. Moraes and colleagues [3] investigated pre-college novice designers' behaviors when leveraging a prescriptive design model—called the "W-model." Students who used the W-model to address a wicked problem demonstrated behaviors associated with "informed designers," where informed designer behaviors are defined by a framework from Crismond and Adams' synthesis of design literature [16].

2.2 Evaluations, Limitations, and Interpretations of Design Process Models

Eckert and Stacey [17] argued that the primary function of prescriptive process models is to enable designers to infer what they should do to be successful rather than be an accurate representation of practice. They suggested that it is beneficial to discuss design process models in terms of their appropriateness or whether they are "fit for purpose," rather than speaking about design process models in terms of their accuracy or correctness.

All design process models are abstractions, abstractions that are created by people with specific intentions who choose to represent those aspects of a design process that they deem important, necessarily excluding other aspects [17]. Relatedly, Wynn and Clarkson [2] highlighted that there is no one, all-encompassing descriptive or prescriptive model. It is particularly important to note that across process models used in engineering, many of the elements left out of design process model visualizations are social and contextual aspects (e.g., see [18, p. 130], [19, p. 2]). This dearth of social and contextual considerations in visual representations aligns with how engineering work has been characterized as having a "technical/social dualism" [20]–[22], which refers to how engineers prioritize "technical" dimensions of their work while devaluing "social" aspects of their work such as interpersonal communication and considerations of public welfare, as well as how engineering culture has historically been, and in many ways continues to be, characterized by the idea that engineering is purely "technical" and thus asocial and apolitical [23].

In Eckert and Stacey's work [17], they noted that across all the engineers they discussed models with—spanning several studies [24]–[26]—all of them assumed that their interpretation of the model was "the" interpretation, when in fact there were differences in how different engineers interpreted the model. They argued that design process models are interpreted, conceptualized, or understood by their users based on several factors, including individuals' previous experiences, priorities, and whether they view the process model as a mandate or a guideline.

3. METHODS

3.1 Research Goals

Our research is conducted from the perspective that every engineering design outcome may affect particular people and/or the public at large. Thus, engineers are responsible for considering social and contextual aspects in their design work. Given the dearth of social and contextual considerations in design process model visual representations, combined with the complexity of problems with which engineers are faced, we aimed to investigate ways in which upper-level mechanical engineering students perceived three different design process models that have prescriptive traits. The following research questions guided our research:

1. How do upper-level mechanical engineering students perceive the usefulness of various design process models?
2. Beyond usefulness, how do upper-level mechanical engineering students differentiate various design process models?

Since our research questions are concerned with understanding the specific ways in which participants perceive design process models, we leveraged qualitative methods (see [27]). Therefore, rather than generalizing our findings to a larger population, we sought to enable readers to determine whether our findings are transferrable to their particular contexts through detailed, contextual descriptions of our data [28].

3.3 Participants

Participants were recruited from a public Midwestern university. Recruitment was limited to upper-level mechanical engineering students to ensure participants had completed some design coursework and reduce the number of potential factors influencing student perceptions.

Our study included six participants. Small-scale qualitative studies are recommended for exploratory research [27], [29]. One example in the literature is the data in Mondisa's [30] exploratory research on mentoring approaches consisted of interviews with ten African-American science, technology, engineering, and math (STEM) Ph.D. mentors. Our small sample size enables our ability to provide contextualized details of the ways in which our participants perceived each of the three process models.

Participants included five fourth-year mechanical engineering students and one fifth-year mechanical engineering student. Five of the six participants had a minor. All participants had completed the first two of a three-course design and manufacturing sequence, five participants were in the process of completing or had just completed the third course in that sequence, and one participant had completed an elective course on front-end design. Five participants had some engineering-related co-curricular experience with co-ops, internships, and/or project teams. Participant ages ranged from 20 to 22 years. Demographic information was collected via open-ended questions on a recruitment survey. Three of the six participants reported their gender as male, two participants reported their gender as female, and one participant reported their gender as woman. One participant reported their race/ethnicity as Asian, one reported their race/ethnicity as Guyanese, three reported their race/ethnicity as White, and one participant reported their race/ethnicity as White/Asian. Participant characteristics are summarized by recruitment criteria in Table 1.

Table 1: SUMMARY OF PARTICIPANT CHARACTERISTICS BY RECRUITMENT CRITERIA

Recruitment Criteria	Participant Characteristics (Participant Count)
Year of Undergrad	4 (5); 5 (1)
Major	Mechanical Engineering (6)
Co-Curricular Experience	Co-ops or Internships (4); Project Teams (5)
Age	20 (1); 21 (4); 22 (1)
Gender	Male (3); Female or Woman (3)
Race/Ethnicity	Asian (1); Guyanese (1); White (3); White/Asian (1)

3.4 Data Collection

Individual semi-structured interviews were conducted with each participant. Interviews were conducted via Zoom, audio-recorded, and automatically transcribed by Zoom. Over the course of the interview, participants were presented with three process models: a Socially Engaged Design (SED) Process Model [31], the first three phases of an engineering design process (EDP) from Dieter and Schmidt [32, p. 15], and a spiral development of mechanical systems (SPIRAL) from Ullman [33, p. 115]. Our focus on design process models that have prescriptive aspects aligns with Ericsson's [34] research that suggests that intentional practice is a key contributor to the development of expertise. We recognize that process models can exist on a continuum from descriptive to prescriptive, and we are not categorizing the process models used in this study as *only* prescriptive but rather acknowledging our focus on the prescriptive aspects of the process models.

Two of the three process models—one representing the design activities that make up the first three phases of an engineering design process [32, p. 15] and one representing the spiral development of mechanical systems [33, p. 115]—were selected from textbooks based on the typical use of those textbooks in junior- and senior-level engineering design courses [35]. The third process model—a Socially Engaged Design Process Model [31]—was selected because it addresses aspects—e.g., designer reflection on their power [36], [37], incorporation of broader contextual considerations [38], [39], and the use of prototypes throughout a design process [40]–[42]—that are often missing from design process models (e.g., [5], [8]).

Each process model was individually presented. Participants were given a few minutes to take in the model and write notes about it and then asked several questions about their impressions of the model. The presentation order of the three process models was counterbalanced across the six participants, as shown in Table 2, to account for order effects.

Table 2: SUMMARY OF PROCESS MODEL PRESENTATION ORDER BY PARTICIPANT

Presentation Order	Participant
123	1
132	4
213	3
231	5
312	2
321	6

Key: 1 = Socially Engaged Design Process Model; 2 = Engineering Design Process; 3 = Spiral Development of Mechanical Systems

The present study includes the data from the end of these semi-structured interviews where participants could see all three process models and were asked several questions aimed at prompting participants' comparison of the models. The comparison questions consisted of:

- Can you talk through what situations each of the models would be helpful for in comparison to the other models?
- Which model or models would you choose to use in your current design work? Why?
- Which model or models would you choose to use in your future design work? Why?
- As you look across this collection of three process models, what similarities and differences do you notice?

It is important to note that participants were only shown visual representations of the process models, their names, and citation (in Author, Year format). They received no verbal or written descriptions of the models. The visual representations presented to participants are shown in Figures 1-3.

At the end of each interview, participants were also asked about their familiarity with each of the three process models. For each of the three models, some participants had, at least potentially, seen the model previously. We summarize this information in Table 3: "Unsure" means that a participant's response indicated that a process model seemed familiar or similar to something they had seen before, but they could not recall if they had seen the exact same process model.

Table 3: SUMMARY OF PARTICIPANT FAMILIARITY WITH PROCESS MODELS

Cite	Process Model	# of Participants
[31]	Socially Engaged Design Process Model	Y (2); N (4)
[32]	Dieter & Schmidt's Engineering Design Process	U (2); N (4)
[33]	Ullman's Spiral Development of Mechanical Systems	U (3); N (3)

Key: Y = Yes; U = Unsure; N = No

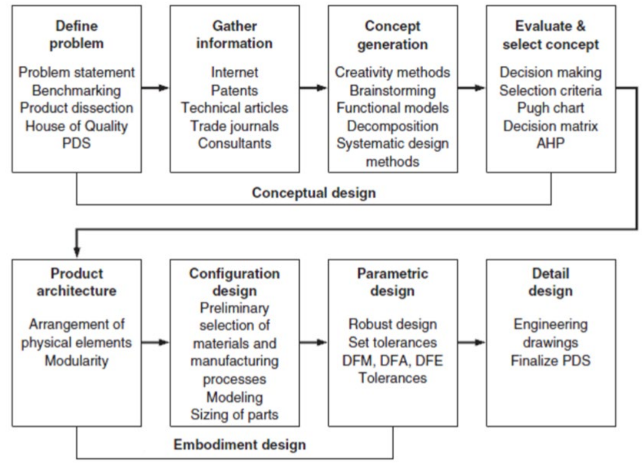

Figure 2: DIETER AND SCHMIDT'S FIRST THREE PHASES OF AN ENGINEERING DESIGN PROCESS [32, p. 15]

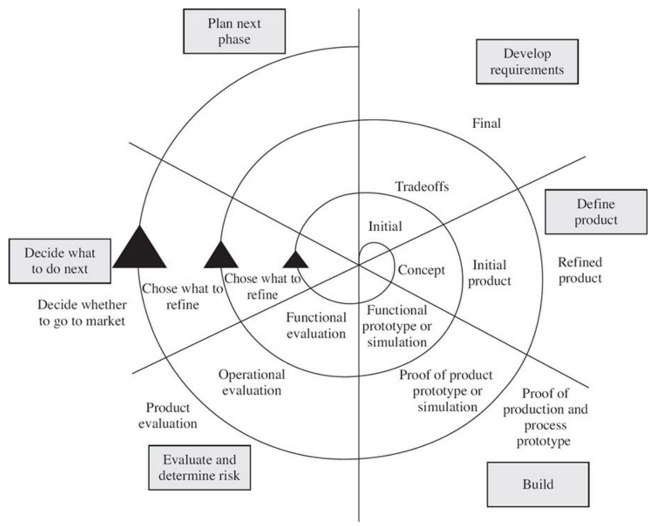

Figure 3: ULLMAN'S SPIRAL DEVELOPMENT OF MECHANICAL SYSTEMS [33, p. 115]

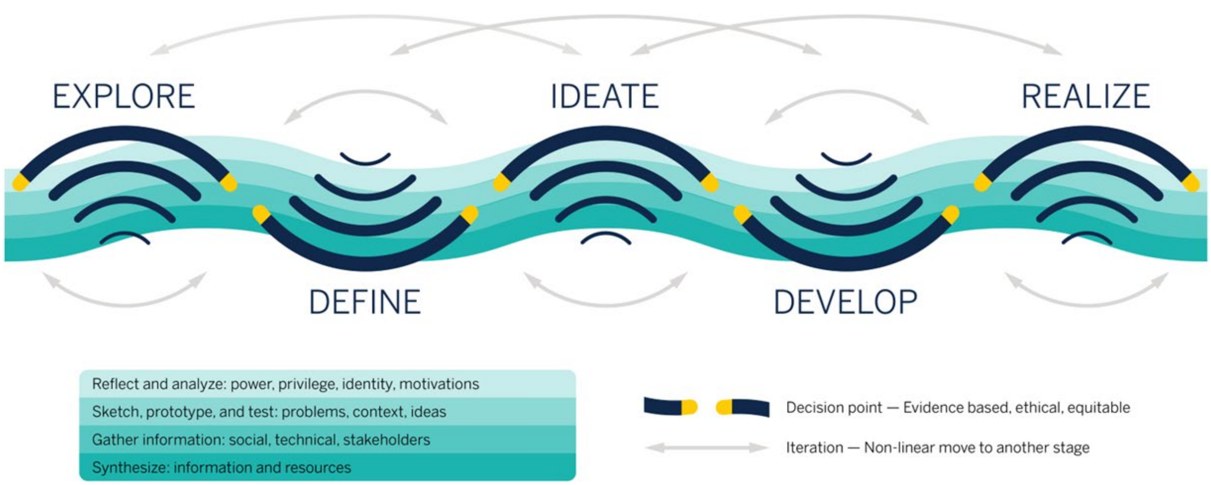

Figure 1: CENTER FOR SOCIALLY ENGAGED DESIGN'S SOCIALLY ENGAGED DESIGN PROCESS MODEL [31]

3.5 Data Analysis

Our process for data analysis was informed by Braun and Clarke's [43] step-by-step guide. First, the Zoom-generated transcripts were reviewed, corrected, and reformatted. We then conducted a thematic analysis to explore upper-level mechanical engineering students' perceptions of three design process models, particularly the similarities and differences between the process models. This process included one researcher: 1) writing analytic memos with descriptive summaries of the data to condense each participant's data and facilitate comparison across participants, guided by Saldaña's manual [44], 2) reviewing the memos and initially coding the data following descriptive and simultaneous coding processes, also guided by Saldaña's manual [44], and 3) matching full data excerpts with the initial codes and further refining the coding scheme. These excerpts, along with the memos, were then reviewed with the goal of findings themes. Potential themes were initially generated and then iteratively refined by collating extracts in a spreadsheet that mapped themes to each participant and discussing themes with the research team.

4. FINDINGS

In addition to usefulness, we identified two salient themes on how our participants perceived a collection of the three design process models. We describe these themes in the following subsections with example quotes from participants' interviews.

4.1 Usefulness

Across participants' responses, we identified eight dimensions they described as distinguishing the usefulness of each process model. Usefulness was defined as the situations and purposes for which participants described a model as helpful or valuable. The eight dimensions of usefulness and how they show up in the three different process models are summarized in Table 4.

The first three dimensions—impacts considered, project scope, and stakeholder interactions— highlight several ways in which social (including interpersonal interactions with stakeholders and broad social context considerations) aspects, or lack thereof, affected the perceived usefulness of the process models. The way five participants discussed the Socially Engaged Design (SED) Process Model emphasized its value in situations where the design outcome would impact society and/or people, including consumer products. For example, Participant 2 described the SED model as considering the "social context:"

Even when thinking about "does it solve the problem," it's like, "does it solve the problem in a way that helps people and doesn't hurt people."

For the spiral development of mechanical systems (SPIRAL) model, three participants concluded it conveyed a focus on consumers from a market analysis perspective. Participant 5 described the SPIRAL model as useful for consumer products "because it does also have… some market research."

Two participants described Dieter and Schmidt's engineering design process (EDP) model as very specific and technical. Participant 5 said:

[EDP] might be specific to a certain field, because there's not really…consideration for impacts…[EDP] primarily focuses on the technical aspects.

Participant 4 had a similar perception. He described the EDP model as helpful for "some type of very specific, like mechanical design… It's very technical."

Two participants described the SPIRAL model as being similar to the EDP model. For example, Participant 5 described the SPIRAL model as helpful for the "production of things that would be more involved in a specific industry." She perceived the SPIRAL model to be both like the SED model and the EDP model. It could be useful for consumer products (see above) and could be useful within the context of a specific industry, respectively.

Three participants highlighted that the SED model would be useful in situations that, as Participant 3 said, have "to do with social engagement." Participant 6 described the SED model as applicable when:

Working with a community… working with people… touching base with… stakeholders throughout the process…

Table 4: SUMMARY OF PROCESS MODEL USEFULNESS BY EIGHT DIMENSIONS

Dimension	SED	EDP	SPIRAL
Impacts considered	Social Impact	-	Market Impact
Project scope	-	Specific & technical	Specific & technical
Stakeholder interactions	Working with people	Not working with people	-
Problem definition	Not defined	Well-defined	Not defined
Project deliverable	-	Drawings or Prototype	Product
Solution novelty	Innovation	-	Known solution
Solution type	Not limited to physical products	Limited to physical products	Limited to physical products
Process applicability	Any process	-	Any process

Key: SED = Socially Engaged Design Process Model; EDP = Engineering Design Process; SPIRAL = SPIRAL development of Mechanical Systems

In contrast, Participant 4 described the EDP model as applicable when "research was the main information source, rather than any kind of user input."

The following four dimensions in Table 4: problem definition, project deliverable, solution novelty, and solution type, demonstrate how an understanding of the problem and/or solution impacted the perceived usefulness of the three process models. Participant 1 described the SED model as helpful for situations:

Where you have a very broad problem statement… know very limited information about the design… don't have very specific requirements for the design already…

In contrast, Participant 1 said EDP would be helpful when:

You're given [a nice and defined] problem statement… you know exactly who your stakeholder[s] are, and… [it] outlines a lot of requirements for you.

Participant 2 compared the SPIRAL model with the EDP model along the problem definition dimension. She talked about how the "super linear" nature of the EDP model meant designers would have to be thorough with each phase, while she thought the SPIRAL model allowed for repeated returns to previous stages. One implication of this allowance that Participant 2 noted was that requirements do not have to be fully defined right away.

Several participants pointed out that the EDP process model would be useful in situations that ended with drawings or creating a prototype. For example, Participant 6 said the EDP model is "good for defining what [a company] want[s], but then having someone else carry it out." Participant 3 showed a similar perception of the EDP when comparing it to the SPIRAL model. When describing what situations each of the models would be helpful for, she said:

[SPIRAL] focuses on something that's larger, broader process, and has the end goal of maybe going form product prototype to product straight up, whereas [EDP] just reaches the prototype phase.

Two participants discussed how a process model would be useful depending on how novel the solution was. Participant 4 described the SED model as being:

Good for innovation or… figuring out something new to create because… in the other models there's nothing that asks you or recommends to explore.

Differently, Participant 6 described the SPIRAL model as:

Definitely good for…a problem [where] you know the solution, or at least like an area of the solution, and you want to work through something to take to the market.

Within the solution type dimension, two participants highlighted how the SED model seemed like it allowed for non-physical solutions. Participant 5 shared that the SED model "was more focused on the safety for the consumer, than it was… [on] specific features." Participant 6 thought the EDP and SPIRAL process models "wouldn't necessarily apply" if the project was not focused on a physical product, but thought the SED model could be used.

Finally, a few participants discussed how broadly applicable a process model was. Participant 4 described the SED model as "a general design process for any problem," while Participant 2 described the SPIRAL model as:

Useful for just any engineering design process because it's so vague and you can kind of shape it to whatever your product would require.

4.2 Iteration

All six participants used iteration as a criterion for comparing the process models. Across these participants, there was agreement that the EDP process model did not illustrate iteration, or at least did not suggest much iteration. Four participants described the EDP model as "linear." On the other hand, participants consistently described the SED model as displaying or encouraging iteration.

Furthermore, most participants described the SPIRAL model as having a focus on iteration, but when comparing all three models in terms of iteration, Participant 4 said:

The iteration in [SED] is very different from [SPIRAL] and [EDP]. Just because there doesn't seem to be much iteration in [SPIRAL] and [EDP], and there is a lot [of iteration] in [SED].

Another facet of the iteration criterion appeared to be how "open" or flexible iteration was within a process model. Two participants described the SPIRAL model as having less flexible iteration than the SED model. For example, when describing differences between the models, Participant 2 said:

[In SED] you can skip phases… [in SPIRAL] you go back to [phases], but you have to go through all the other ones first.

Differently, Participant 1 perceived the SPIRAL model's iteration to have flexibility similar to that of the SED model:

In the sense that you can…jump from 'choose what to refine' back to 'tradeoffs' and stay in that loop if you need

Participant 5 noted how the design process models shifted from a focus on conceptual design to "solid" design to describe the differences in iteration across the three models. She positioned the SED model as the most "open," followed by the SPIRAL model and then the EDP model.

[EDP and SPIRAL] both go conceptual to a solid design. But, and then [with SED], you sort of can keep going back to the

conceptual model and make updates as needed. And then [SPIRAL] [is] more open than [EDP], I think, when looking back at initial design choices, because of the loop, but it still sort of has that, the conceptual to solid design.

4.3 Level of Detail

Four participants compared the three process models based on their inclusion of specific methods to support the various stages of the models. Across these participants, the EDP model was described as having more detail or more specific steps than the SED model. However, there was variation in how the SPIRAL model was positioned relative to the EDP and SED process models.

Participant 1 differentiated the EDP model from the SPIRAL and SED models, stating:

Some differences [between the models] would be [EDP], when compared to [SED] and [SPIRAL], does a better job of describing what methods can be taken in those phases.

In contrast, Participant 6 differentiated the SED model from the EDP and SPIRAL models. For example, Participant 6 said:

[SPIRAL] and [EDP] talk more about specific steps within each stage, whereas [SED] is [saying] go through the stage a few times, but [SED] doesn't talk about the different steps for it.

Finally, Participant 3 differentiated all three models based on how much detail was in each model:

[EDP] breaks down the broader steps in a lot of detail… [SPIRAL] is less descriptive in terms of considerations for each step along the way… [EDP] and [SPIRAL] do have more descriptive statements for each of their parts [relative to SED].

5. DISCUSSION

Participants' perceptions of the three process models highlight several ways in which the process models vary in terms of their use, their communication of iteration, and their level of detail. This variation aligns with prior work that highlights how process models vary in terms of what they include and what they represent about a design process [17].

One particularly salient dimension of usefulness that highlighted differences between the three process models was "impacts considered." Five participants discussed how the SED model would be useful where the design outcome would impact society and/or people. In comparison, three participants concluded the SPIRAL model focused on consumers from a market analysis perspective. Although consumer products were named as one situation in which the SED model would be helpful, we—along with others (e.g., [45]–[48])—argue that every engineering design outcome could impact people and/or society broadly. Thus, engineers are responsible for integrating considerations of such impacts in their work. It is important for design researchers and process model creators to recognize that consideration of market impacts does not equate to considering a diverse range of potential impacts on society and people. Consideration of social impacts necessarily includes considering market impacts, but consideration of market impacts does not necessarily include consideration of other social impacts—e.g., ethical implications, environmental impacts, implications of public use.

Another dimension of usefulness was "stakeholder interactions." Three participants highlighted that the SED model would be useful when working with people. While finding that a socially engaged design process model has "to do with social engagement" (Participant 3) is perhaps an unsurprising finding on its own, we find it particularly compelling that participants did not name working with people in either the EDP or SPIRAL model. In fact, Participant 4 described the EDP as useful for situations where "research [is] the main information source rather than any kind of user input." The EDP and SPIRAL models do not necessarily preclude stakeholder engagement, but our findings illustrate they these models are not making stakeholder interactions a salient part of design. In contrast, the SED model sets students up to consider working with people by making social engagement explicit.

Dieter and Schmidt's textbook that includes their EDP model discussed that "the design process should be conducted so as to develop quality, cost-competitive products in the shortest time possible," [32, p. 5]. In Ullman's textbook that includes the SPIRAL model, Ullman stated, "There is a continuous need for new, cost-effective, high-quality products… To complete in this [global] market, a company must be very efficient in the design of its products," [33, p. 2]. Finally, members of the Center for Socially Engaged Design, who created the SED process model, described "the goal of socially engaged design within engineering" as "to equitably address complex societal challenges through collaborative, reciprocal relationships that build upon deep analyses of design context, positionalities, and technical knowledge," [49]. Recognizing that the three process models were created by different people with different purposes, it is not surprising that we saw variation in the models through the lenses of our participants' perceptions.

Another finding was the ways in which the SPIRAL model was perceived as similar to and different from the SED model as well as similar to and different from the EDP model. In terms of usefulness, SPIRAL was perceived to be similar to SED in that it would be helpful to consider some impacts, be helpful for when a problem is not well-defined, and be applicable to "any engineering design process" (Participant 2). On the other hand, SPIRAL was perceived to be similar to EDP in terms of having a specific and technical project scope and being limited to physical products. In terms of iteration, most participants described the SPIRAL model as focusing on iteration, which paralleled participants' consistent descriptions of the SED model as encouraging iteration. However, Participant 4 described the SPIRAL model as being similar to the EDP model in that there did not "seem to be much iteration." When it came to how flexible the iteration was, one participant described the SPIRAL model as having similar flexibility to that of the SED model, while a couple participants described the SPIRAL model as having less flexibility than the SED model. Finally, in terms of how detailed the models were, across four participants we saw the SPIRAL model positioned as (1) having less detail than EDP, but similar detail to SED, (2) having similar detail to EDP and more detail than SED, and (3) having less detail than EDP, but more detail than SED.

This variation in our six participants' perceptions of the same process model echo findings summarized in Eckert and Stacey's work [17], where engineers interpreted the same model differently and in [49] where students' interpretations of a process model at times differed from what the process model creators intended. An important consideration for both design process model creators and engineering educators who leverage design process models is that models are subject to users' interpretations and therefore, there is inherently room for misconceptions and/or alternative interpretations than what is intended.

One way to support students conceptual understanding of design processes could be to discuss and negotiate the meaning of process models, following Treagust et. al.'s [50] investigation of two classes of students—one taught analogically and one not—and Perry's [51] models of intellectual and ethical development. Students should be warned about the limitations of models—i.e., there is no single model of a design process—in alignment with how there can be no single model of any process [52]. Furthermore, as each process model necessarily includes some aspects of a design process while leaving others out [17], [53], leveraging multiple models has been recommended for science and mathematics educators [53], [54] and characterized as an expert modeling ability in science contexts [55]. Leveraging multiple design process models in engineering courses could communicate the limitations any single design process model and help scaffold design students understanding of what it means to design.

5.1 Limitations

Process model visualizations can be used as a quick reference when engaging in design and, based on the principle of salience [56]–[59], serve as a proxy for the most important aspects of the processes they illustrate. Process models visualizations often have text-based descriptions, elaborations, and/or explanations of the process model. However, there can be variation in how much text is provided. In the context of our research study, we were particularly concerned about the amount of text biasing student responses and significantly increasing the length of our interviews. For example, students may have had more to say about models that had more provided text and text selection would be an ambiguous process given the various materials that cover the process models in our study (e.g., textbooks, websites, slides/presentations). In order to support comparability of the three process models, we decided to only share visual representations of the process models with participants. Thus, one limitation of our study is that we are only capturing participants perceptions of the visualizations of the three process models, knowing that the visualizations may contain a subset of all available information about a particular process model [60].

Another study limitation was that we only collected data from participants in a single interview; it is possible that participants' perceptions of the models would change if they were given more time to review the models and/or engage in a design process while leveraging each of the models. Finally, usefulness, iteration, and level of detail were the most salient differentiators across our participants and do not necessarily cover all potential differentiators of design process models.

5.2 Implications

The findings of this study suggest that students would benefit from multiple models, including models that recognize the social aspects of design work. Leveraging models that acknowledge society and people in engineering design decision-making can support educators in conveying the relevance of considering social aspects in one's role as an engineer. Without other tools or support that name the importance of social considerations in design, students are likely to continue to struggle to attend social complexity as they have in the recent past (e.g., [61], [62]).

6. CONCLUSION

Our study explored upper-level mechanical engineering students' perceptions of three design process models. We conducted semi-structured interviews with six participants who were presented with only the visual representations of the three process models; no text-based description was provided. From our thematic analysis of participants' interview transcripts, the most salient differentiating aspects of student perceptions of these process models were use, iteration, and level of support. Variations in student perceptions highlight the importance for accounting for individuals' varying interpretations of process models as well as the benefit of leveraging multiple process models in engineering design curricula.

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