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NOVICE DESIGNERS' APPROACHES TO JUSTIFYING USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

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ABSTRACT

User requirements and engineering specifications represent important criteria that engineering designers use to define their design problems and evaluate the suitability of their solution concepts. Novice designers frequently develop user requirements and engineering specifications as part of curricular design projects; however, few studies have explored how novice designers justify the user requirements and engineering specifications that they develop. This preliminary study analyzed the design reports of capstone design teams to determine how novice designer participants justified their user requirements and engineering specifications. Teams frequently used "Sponsor interactions" and "Perceptions of user needs" as justifications for user requirements but gathered limited data directly from users. As such, the user requirements developed by teams may have been based on team assumptions rather than actual user needs. Teams frequently used "Sponsor interactions," "Technical research," and "Prior work" as justifications for engineering specifications. However, teams also developed several engineering specifications without clear justifications. Our findings suggest that as novice designers develop their design skills, they may need scaffolding and support tools to guide the development of user requirements and engineering specifications that accurately reflect user needs.

Keywords: Requirements, specifications, design decision-making, novice designers, capstone design

1. INTRODUCTION

The development of user requirements and engineering specifications is a key component of engineering design processes [1–3]. User requirements describe qualitative needs or wants that users may have for potential solution concepts [1,2], while engineering specifications translate user requirements into quantified, measurable design parameters that engineering designers can use to evaluate the suitability of their solutions [1,3]. The development of user requirements and engineering specifications may be informed by several different types of information, including data gathered from stakeholders, contextual research, academic literature, professional standards, expert advice, and benchmarking of existing products [1–4].

Novice designers are frequently tasked with developing user requirements and engineering specifications in curricular design contexts such as capstone courses [5–8]. However, few studies have explored how novice designers justify design decisions related to developing user requirements and engineering specifications. As a result, the specific ways that novice designers leverage information gathered from stakeholders, contextual research, and other sources when identifying and refining their user requirements and engineering specifications is unclear. It is also unclear to what extent novice designers validate that their user requirements and engineering specifications align with true user needs. The goal of this preliminary study was to address this knowledge gap by exploring how capstone design teams justified the user requirements and engineering specifications that they developed in their design reports.

2. BACKGROUND

2.1 User Requirements & Engineering Specifications

User requirements and engineering specifications represent two distinct but related ways of synthesizing information gathered from stakeholders, contextual research, and other relevant resources into specific design parameters [1–3]. The development of user requirements and engineering specifications can help designers define their design problem and identify important solution criteria [1–3].

User requirements are qualitative criteria that represent the user's opinion of solution quality, often based on the user's own

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words [1,2]. User requirements thus represent broad goals that designers should seek to achieve when developing solutions. Several frameworks, such as Garvin's Eight Dimensions of Quality [2,9], exist to guide requirements development. In addition, several engineering design textbooks recommend that designers verify user requirements with users throughout their requirements development process, for instance by continuing to collect data and user input related to user requirements, to make sure that identified user requirements accurately reflect user needs and wants for potential solutions [1,2].

By comparison, engineering specifications are the restatement of user requirements in terms of measurable, quantitative parameters with target values [1,3]. Engineering design textbooks recommend that an effective engineering specification should be verifiable, meaning that it is possible to evaluate whether the engineering specification has been met, and solution-neutral, meaning that fulfillment of the engineering specification does not rely on the implementation of a specific solution [1,3] (see also [10]). There are several ways that a user requirement might be restated as an engineering specification, as demonstrated in Table 1. Ullman recommends that designers first generate many potential engineering specifications for each user requirement before narrowing down to the engineering specifications that are most contextually relevant [1].

TABLE 1: EXAMPLE OF USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS TABLE, ADAPTED FROM [11]

User Requirements	Engineering Specifications
Durable	1. Device should withstand more than 5950 uses before failure 2. Device should contain fewer than three consumable parts 3. Device power source must last a minimum of 120 minutes before recharge
Easy to use	1. Device must require no more than one operator to operate 2. New user should be able to learn correct device operation procedure successfully in less than 138 seconds
Portable	1. Device dimensions must not exceed 31.8 cm x 24.77 cm x 16.19 cm 2. Device weight must not exceed 4.79 kg

2.2 Novice Designer Approaches to Developing User Requirements and Engineering Specifications

Several studies have explored novice designer approaches to developing user requirements and engineering specifications. For example, Mohedas, Daly, and Sienko [4] investigated how novice designers gathered and used information to develop user requirements as part of a simulated design task. This study found that the validity and level of tailoring of the user requirements developed by novice designers was closely related to the number of distinct information sources that novices consulted [4]. Other studies have found that direct interactions with users can help novice designers develop more appropriate solution concepts, in part due to a better understanding of user requirements [12,13].

Previous studies have also described several novice behaviors that might negatively impact novice designer approaches to requirements development. Novice designers may spend limited time on problem definition activities, including developing user requirements [14]. Novice designers may also consult fewer information sources than initially intended due to struggles connecting with stakeholders who can provide relevant information and/or struggles translating stakeholder responses into specific user requirements or engineering specifications [5,6]. Furthermore, novice designers may encounter difficulties leveraging prototypes – for example, sketches or low-fidelity models with which stakeholders can interact [15] – as effective tools for identifying and defining their user requirements or engineering specifications [16]. Finally, there are several categories of information, such as those relating to safety and accessibility, that novice designers may consider less relevant and subsequently underexplore [17,18]. Each of these difficulties could lead novice designers to make inaccurate assumptions about users that in turn affect their user requirements and the suitability of their solutions [12,17,19]. However, previous studies have not specifically described how the novice behaviors described above impact novice approaches to making and justifying design decisions related to user requirements and engineering specifications. Detailed information about novice decision-making processes is thus needed to develop effective support structures for novice designers engaged in developing user requirements and engineering specifications.

3. METHODS

3.1 Research Questions

The goal of our study was to explore how novice designers justified the user requirements and engineering specifications that they developed in their design projects. Our study was guided by the following research questions:

1. How do teams of novice designers justify the user requirements and engineering specifications that they develop for their design projects?
2. How often are specific justifications for user requirements and engineering specifications used across different novice design teams?
3. How do novice design team justifications for user requirements and engineering specifications change over the course of their design projects?

3.2 Participants and Design Context

Data for our study were collected as part of a larger study exploring how capstone design teams gathered information to inform their projects [19,20]. Participants included 34 students comprising eight design teams enrolled in two sections of a single-semester senior-level capstone design course at a large Midwestern university (Table 2). This is a large sample of teams compared to similar studies of novice designers' requirements development practices in capstone settings (e.g. [6,7]).

TABLE 2: LIST OF PARTICIPATING TEAMS

Team	Capstone section	Type of project	Sex of team members	Race/Ethnicity of team members
A	1	Developing assistive device	1F, 2M	1 Asian, 1 Hispanic, 1 White
B	1	Developing assistive device	1F, 4M	3 Asian, 2 White
C	1	Developing assistive device	1F, 4M	2 Asian, 3 White
D	2	Modifying university space	1F, 3M	4 White
E	2	Developing measurement tool	3M	3 White
F	2	Modifying university space	4M	4 White
G	2	Developing medical device	4M	4 White
H	1	Developing measurement tool	4F, 2M	6 White

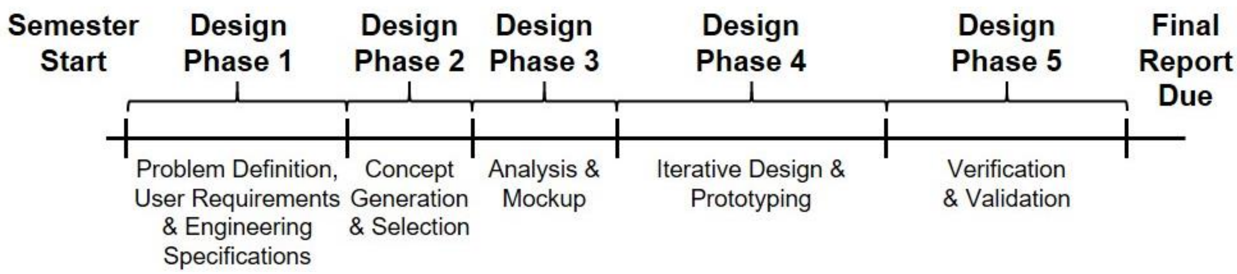

FIGURE 1: TIMELINE OF DESIGN PHASES FOR CAPSTONE COURSE

Each design team was tasked with developing a prototype to solve a unique design problem experienced by a project sponsor. Teams A, B, and C were also assigned specific end-users for their prototype. Each team included three to six undergraduate students majoring in mechanical engineering, all of whom had completed the required two-course mechanical design sequence as part of their previous education. Many participants also described exposure to additional design experiences through internships, co-curricular projects, and design electives.

Studying novice engineering designers in a capstone design course provides a lens for understanding how early career practitioners may approach design tasks. Capstone courses often represent a final curricular experience that teaches undergraduate engineering students how to apply their engineering knowledge in practice [21,22]; the behaviors that novice designers exhibit in capstone environments thus may be indicative of how they will approach similar design tasks in their early professional work.

The capstone course from which we recruited participants spanned several design stages including problem definition, concept generation and selection, design iteration and prototyping, and verification and validation (see Figure 1), although expectations for these different stages varied slightly by capstone section (each section was taught by a different mechanical engineering professor) and project type. Each team began the semester with a brief project description identifying a subset of the design attributes of an effective solution. However, since the information included in the project descriptions was incomplete, the capstone context provided an opportunity for us to study how novice designers gathered additional information about their design problems, synthesized this information into user requirements and engineering specifications, and iterated on their user requirements and engineering specifications across multiple design stages.

Teams attended a standard lecture on requirements development practices during Design Phase 1 of the capstone course. The instructional material described several information sources that teams might leverage to develop user requirements and engineering specifications (e.g., standards, interview data, or benchmarking), as well as different methodologies (e.g., Quality Function Deployment [1–3]) and frameworks (e.g., Garvin's Eight Dimensions of Quality [9]) that might assist teams in their requirements development processes. The capstone instructors also stressed the importance of validating user requirements and engineering specifications using input from project stakeholders to ensure that potential solution concepts would meet actual user needs. Capstone section instructors provided informal feedback to teams on their user requirements and engineering specifications during weekly project meetings and formal feedback through written and oral design reviews.

3.3 Data Collection

Teams submitted four design reports as part of their capstone course. The timing and content of these design reports aligned with the first four design phases shown in Figure 1 (e.g., Design Report 1 was submitted at the end of Design Phase 1 and focused on problem definition and identification of user requirements and engineering specifications). Teams also submitted a final report compiling their earlier design reports and additional content documenting verification and validation results at the end of the semester. These design reports represented several hundred pages of writing across the eight teams.

Design reports represented an ideal type of data for tracking how novice designers justified the user requirements and engineering specifications that they generated, and have been used as data in previous studies analyzing novice designer processes (e.g., [8,23]). The goal of the design reports and final reports submitted for the capstone course was to provide a traceable record of each team's design decisions. As such, descriptions of team design decisions in the design reports were usually supported with explicit justifications and teams were partially assessed on the quality of these justifications. For example, 30% of each team's grade for Design Report 1 was based on the quality of their documentation related to initial user requirements and engineering specifications. Each design report also built upon and sometimes modified a given team's previous submissions. While teams were encouraged to justify in subsequent design reports the changes that they made to earlier design deliverables, teams did not always do this consistently.

We also collected supplementary data as part of our study, including interviews with teams as well as recordings and timelines of team information gathering meetings. Although these supplementary data did not explicitly investigate team approaches to requirements development, and thus were not included in our analysis, they did provide important contextual information about how the teams in our study gathered the information that they then used to develop their user requirements and engineering specifications. We thus used these supplementary data to verify the findings from our study.

3.4 Data Analysis

We applied an inductive approach to analyze the design reports submitted by the eight teams, meaning that we reviewed the collection of data several times to identify and define key types of justifications for user requirements and engineering specifications that were used repeatedly by participating teams [24–26]. Following Ullman [1], we defined "user requirements" as any statement (other than the statement of the design problem) that teams made about broad goals or criteria that their designs needed to fulfill. We defined "engineering specifications" as any translation of these user requirements into quantified metrics. In some cases, teams provided specific tables that they labeled as containing user requirements and engineering specifications. In other cases, teams described their user requirements and engineering specifications in a paragraph or list format.

Teams often provided explicit justifications when describing their user requirements and engineering specifications. For instance: "Since this project is entirely focused on [End User], several of the engineering specifications' rationales are based on [End User]'s capabilities or explicitly defined wants. For example, the specifications associated with user requirements 1, 2, 10, 11, 12, and 13 get their rationales in this manner." (*Team C, DR1*). While analyzing each team's user requirements and engineering specifications, we grouped together similar types of justifications into distinct categories [24–26]. We then named and defined these categories of justifications based on team language as well as previous accounts of how novice designers justify design decisions. For example, the *Perceptions of user needs* justification category was partially defined in reference to previous work on how novice designers leverage their perceptions of the user to justify design decisions [13,27]. We iterated on our list of justification categories by discussing and resolving discrepancies in how members of our research team categorized participant justifications during our first round of analysis and by building consensus within our research team as to the formal definitions of each justification category.

TABLE 3: JUSTIFICATIONS PROVIDED BY TEAMS FOR THEIR USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Justification	Definition	Example
User Interactions	Justification refers to direct interaction with users	"When meeting with [the user], we determined that he is able to comfortably move his arm in an approximately 40-degree arc." (*Team C, DR2*)
Perceptions of User Needs	Justification refers to user needs as conceptualized by the team	"It is important that the final prototype is ergonomical in design and avoids extensive physical activity. The user should not have to let go of the [device] when [performing the target activity]." (*Team B, DR1*)
Sponsor Interactions	Justification refers to direct interaction with project sponsors (i.e., the individual(s) who initiated the project)	"This leads to the second most important user need: portability… Our sponsor hopes that we can produce a prototype device that has similar dimensions to that of a sizable smartphone." (*Team G, DR1*)
Prior Work	Justification refers to work completed in a previous semester by a prior design team	"Using information obtained from previous work, it was determined that 30 seconds is the upper limit for the [operation] time required by the device." (*Team B, DR1*)
Technical Research	Justification refers to academic sources or engineering analysis performed by the team	"The desired reverberation time range… is 0.8 to 1.0 seconds (Blauert and Xiang 2009). This standard was used to set the team's minimum reverberation time." (*Team D, Final*)
Standards	Justification refers to professional design standards	"The padding [on the device] cannot exceed 1.5 inches (ASTM Standard F2194, 2016)." (*Team E, DR1*)
Constraints	Justification refers to external factors that constrain solution possibilities	"The solution designed must maintain at least the current flow rate to provide sufficient aeration." (*Team F, DR1*)
Unclear	User requirement or engineering specification is described without clear justification	"Run 15,000 tests" (*Team H, DR1*)

Once our list of justification categories was finalized, we reviewed the data a second time to verify that we had identified and correctly categorized all user requirements and engineering specifications developed by teams. At this point, we also labeled all user requirements and engineering specifications that lacked clear justifications as *Unclear*. Finally, two researchers re-coded the first design reports for three teams to determine the inter-rater reliability of our justification categories. Our inter-rater reliability (Cohen's kappa) was 0.86, indicating a high degree of agreement between the two researchers [28,29].

4. FINDINGS

The eight teams in our study developed a total of 84 user requirements and 103 engineering specifications to guide their projects. These totals included the original user requirements and engineering specifications presented in Design Report 1, as well as additions and revisions to user requirements and engineering specifications described in subsequent design reports. Teams provided justifications for 73 (86.9%) of the user requirements and for 65 (63.1%) of the engineering specifications that they developed. Seven main types of justifications were used by teams to support the perceived validity of their user requirements and engineering specifications. These justifications, along with examples, are provided in Table 3. The remaining 11 (13.1%) user requirements and 38 (36.9%) engineering specifications developed by teams were either included in design reports without justification or were not justified in enough detail to be coded using another justification code; an example of this *Unclear* justification category is also shown in Table 3.

TABLE 4: TOTAL NUMBER OF USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS DEVELOPED ACROSS TEAMS, BROKEN DOWN BY JUSTIFICATION

Justification	Total user requirements	Total eng. specifications
User Interactions	3	7
Perceptions of User Needs	23	6
Sponsor Interactions	31	16
Prior Work	8	12
Technical Research	0	15
Standards	3	2
Constraints	5	7
Unclear	11	38
Total	**84**	**103**

4.1 Total Frequency of Justifications for Developing User Requirements and Engineering Specifications

Sponsor interactions (31 times, 36.9% of all requirements) were used most often by teams to justify user requirements. *Perceptions of user needs* (23 times, 27.4% of all requirements) were also frequently used to justify user requirements. The three most used justifications for engineering specifications were *Sponsor interactions* (16 times, 15.5% of all specifications), *Technical research* (15 times, 14.5% of all specifications), and *Prior work* (12 times, 11.7% of all specifications). Less often used to justify user requirements and engineering specifications were *Standards*, *Constraints*, and *User interactions*. Total occurrences of justifications for user requirements and engineering specifications are shown in Table 4.

4.2 Frequency of Justifications Across Teams

Teams adopted a variety of different approaches to justifying their user requirements. For example, although all eight teams justified at least two user requirements in terms of *Sponsor interactions*, one team (H) justified eight (65.1% of their total) user requirements using this justification. *Sponsor interactions* was the only justification used by all teams.

Two other justifications for user requirements, *Perceptions of user needs* (six teams) and *Constraints* (four teams), were used at least once by several teams. Teams C and E in particular justified a large proportion of their user requirements in terms of *Perceptions of user needs*, with Team C using this justification for eight (50% of their total) user requirements and Team E for six (46.2% of their total). These two teams accounted for 60.9% of all user requirements justified in terms of *Perceptions of user needs* and were thus partly responsible for this justification having a high number of total occurrences. *Prior work*, *Standards*, and *User interactions* were used sparingly to justify user requirements, although two teams (A and B) did each use the *Prior Work* justification for at least three of their user requirements. *Technical research* was not used by a single team to justify their user requirements.

TABLE 5: JUSTIFICATIONS FOR USER REQUIREMENTS BY TEAM (TOTAL ACROSS DESIGN REPORTS), SORTED BY TOTAL PREVALENCE

	Teams							
Justification	A	B	C	D	E	F	G	H
Sponsor Interactions	3	5	2	2	4	4	3	8
Perceptions of User Needs	2	4	8	-	6	-	1	2
Unclear	-	2	1	-	1	2	2	3
Prior Work	5	3	-	-	-	-	-	-
Constraints	-	-	2	-	1	1	1	-
Standards	-	1	-	-	1	1	-	-
User Interactions	-	-	3	-	-	-	-	-
Technical Research	-	-	-	-	-	-	-	-
Total	10	15	16	2	13	8	7	13

TABLE 6: JUSTIFICATIONS FOR ENGINEERING SPECIFICATIONS BY TEAM (TOTAL ACROSS DESIGN REPORTS), SORTED BY TOTAL PREVALENCE

	Teams							
Justification	A	B	C	D	E	F	G	H
Unclear	-	7	3	2	11	1	3	11
Sponsor Interactions	1	4	3	-	-	-	4	4
Technical Research	2	2	7	2	-	-	1	1
Prior Work	8	4	-	-	-	-	-	-
Constraints	1	2	3	-	-	1	-	-
User Interactions	-	1	6	-	-	-	-	-
Perceptions of User Needs	-	2	-	-	-	-	-	4
Standards	-	1	-	-	1	-	-	-
Total	12	23	22	4	12	2	8	20

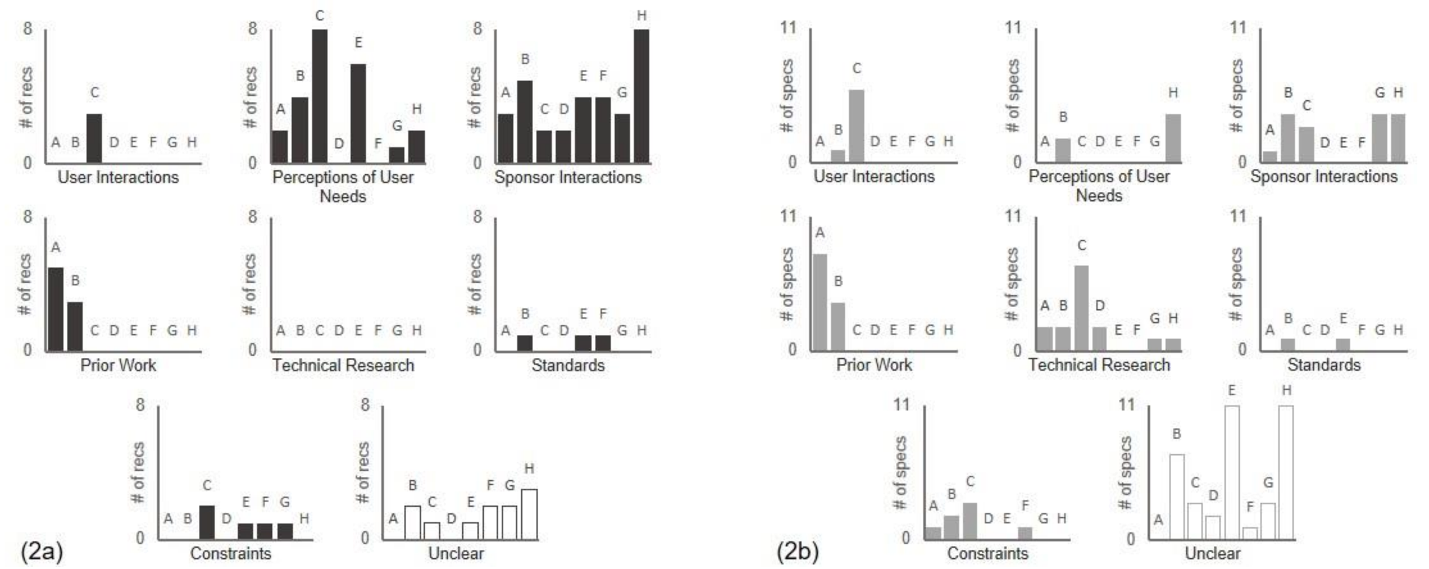

FIGURE 2: JUSTIFICATIONS FOR USER REQUIREMENTS (2a) AND ENGINEERING SPECIFICATIONS (2b) BY TEAM (TOTAL ACROSS DESIGN REPORTS). WHITE BARS DENOTE *UNCLEAR* USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS.

A summary of how each of the eight teams in our study (A-H) justified the user requirements that they developed for their projects is shown in Table 5. A visual representation of these results is shown in Figure 2a.

Teams also adopted various approaches to justifying their engineering specifications. Three justifications were used at least once by several teams: *Technical research* (six teams), *Sponsor interactions* (five teams), and *Constraints* (four teams). Two other justifications, *Prior work* and *User interactions*, were each used a significant number of times by a single team. Eight (66.7% of their total) of Team A's engineering specifications were justified in terms of *Prior work*, which is partially why *Prior work* appeared as a frequent justification for engineering specifications overall. Meanwhile, Team C justified six (27.3% of their total) engineering specifications in terms of *User interactions*, representing almost all total observations of this justification. These results are shown in Table 6 and Figure 2b.

Teams B (seven, 30.4% of their total), E (11, 91.7% of their total), and H (11, 55% of their total) each generated a large number of engineering specifications without clear justifications. These three teams together account for 76.3% of the *Unclear* engineering specifications observed in our study.

4.3 Frequency of Justifications Across Design Reports

The usage of different justifications also varied across the design reports submitted by the teams. Teams identified 73 total user requirements in Design Report 1 (DR1), which focused on problem definition. The most common justifications for user requirements in DR1 were *Sponsor interactions* (29, 39.7% of DR1 total) and *Perceptions of user needs* (20, 27.4% of DR1 total), mirroring the overall proportions discussed in Section 4.1. Minimal additional user requirements (nine) or revisions to previously reported user requirements (two) were noted after DR1. These results are shown in Table 7 and Figure 3a.

TABLE 7: JUSTIFICATIONS FOR USER REQUIREMENTS BY DESIGN REPORT (TOTAL ACROSS TEAMS), SORTED BY TOTAL PREVALENCE

	Design Reports				
Justification	DR1	DR2	DR3	DR4	Final
Sponsor Interactions	29	-	-	2	-
Perceptions of User Needs	20	2	-	-	1
Unclear	6	-	2	-	3
Prior Work	8	-	-	-	-
Constraints	4	1	-	-	-
Standards	3	-	-	-	-
User Interactions	3	-	-	-	-
Technical Research	-	-	-	-	-
Total	73	3	2	2	4

TABLE 8: JUSTIFICATIONS FOR ENGINEERING SPECIFICATIONS BY DESIGN REPORT (TOTAL ACROSS TEAMS), SORTED BY TOTAL PREVALENCE

	Design Reports				
Justification	DR1	DR2	DR3	DR4	Final
Unclear	21	3	2	2	10
Sponsor Interactions	15	1	-	-	-
Technical Research	8	-	3	3	1
Prior Work	12	-	-	-	-
Constraints	6	-	1	-	-
User Interactions	3	3	1	-	-
Perceptions of User Needs	2	-	-	-	4
Standards	2	-	-	-	-
Total	69	7	7	5	15

Teams identified 69 total engineering specifications in Design Report 1, with *Sponsor interactions* (21, 30.4% of DR1 total), *Prior work* (12, 17.4% of DR1 total), *Technical research* (eight, 11.6% of DR1 total), and *Constraints* (six, 8.7% of DR1 total) occurring most often as justifications.

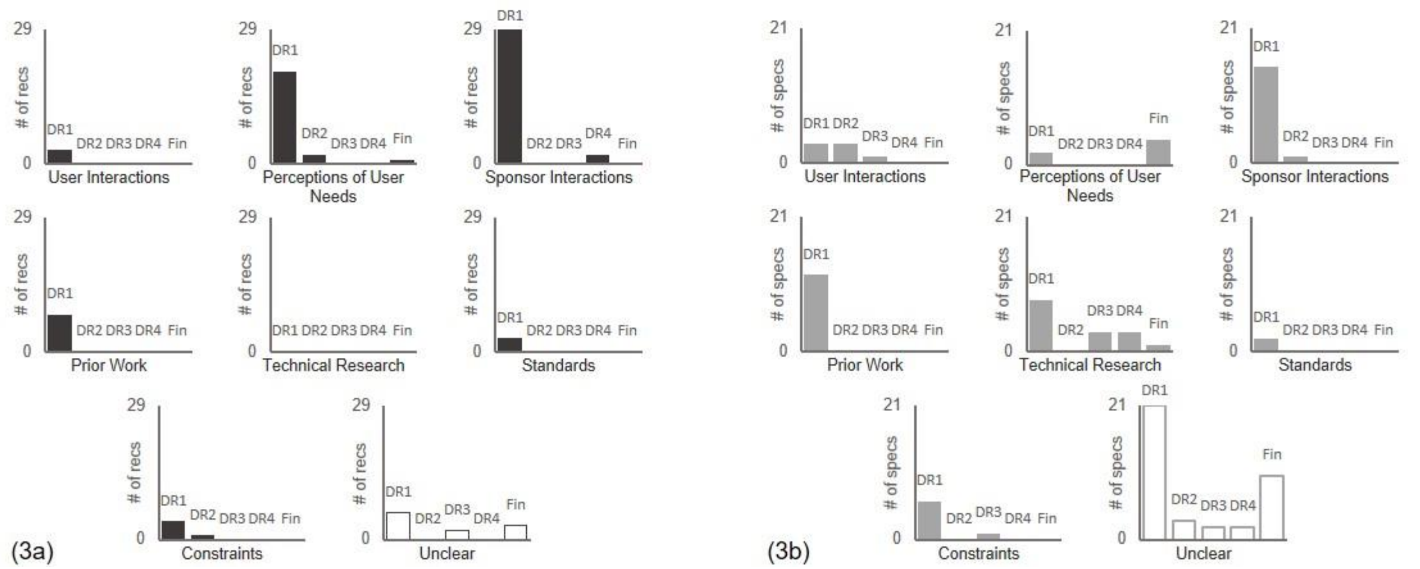

FIGURE 3: JUSTIFICATIONS FOR USER REQUIREMENTS (3a) AND ENGINEERING SPECIFICATIONS (3b) BY DESIGN REPORT (TOTAL ACROSS TEAMS). WHITE BARS DENOTE *UNCLEAR* USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS.

Unlike with user requirements, teams continued to develop their engineering specifications on a small scale through the final design report. Seven justifications relating to the addition of new engineering specifications (six) or revision of previous engineering specifications (one) occurred in Design Report 2, seven justifications (three additions, four revisions) occurred in Design Report 3, five justifications (four additions, one revision) occurred in Design Report 4, and 15 justifications (12 additions, three revisions) occurred in the final report. *Technical research* in particular was used six times (50% of DR3 + DR4 total) to justify additions or revisions to engineering specifications in Design Reports 3 and 4, while *User interactions* was used four times (28.6% of DR2 + DR3 total) to justify additions or revisions to engineering specifications in Design Reports 2 and 3. These results are shown in Table 8 and Figure 3b.

Unclear justifications for engineering specifications were distributed across the design reports and final report. Teams developed 21 (30.4% of DR1 total) engineering specifications with *Unclear* justifications in Design Report 1, three (42.9% of DR2 total) in Design Report 2, two (28.6% of DR3 total) in Design Report 3, two (40% of DR4 total) in Design Report 4, and 10 (66.7% of Final total) in the final report.

5. DISCUSSION

5.1 Justifications Provided by Novice Designers when Developing User Requirements

Teams justified their user requirements in several ways, and the two most common justifications were *Sponsor interactions* and *Perceptions of user needs*. All eight teams justified at least two user requirements in terms of *Sponsor interactions*, meaning that every team claimed to use data collected from sponsors to inform their user requirements. *Sponsor interactions* were also the most common justification stated in Design Report 1, suggesting that teams relied heavily on data from their sponsors to justify their initial user requirements. These findings likely reflect the specific curriculum of the capstone course from which we recruited participants; teams were required to meet with their project sponsors during Design Phase 1 and were encouraged to discuss user requirements and engineering specifications during these initial meetings. However, the prevalence of the *Sponsor interactions* justification in our data is still noteworthy for two reasons. First, teams had access to many other types of information, such as standards or benchmarking of existing products, that they could have also used to justify their user requirements. Second, our findings seem to counter previous accounts of capstone design teams' resistance to leveraging stakeholders as data sources to inform their projects [21,30]. The structure of the capstone course featured in this study may thus have led teams to include stakeholder perspectives in their requirements development processes to a greater extent than they might have otherwise.

Six teams justified at least one of their user requirements in terms of *Perceptions of user needs*, following recommendations that user requirements should reflect the needs of the user [1,2]. However, these user requirements were based on the *teams'* understanding of what their users needed; justifications based on direct observational or interview data with users would have aligned with the *User interactions* category instead. Of the six teams who used the *Perceptions of user needs* justification, only Teams B and C gathered data from users, partially because these two teams were assigned users as part of the capstone course [19]. Team A was also assigned a user but did not interact with the individual. Meanwhile, Teams E, G, and H seem to have used the *Perceptions of user needs* justification based on the needs of imagined users; Team E in particular used this justification for almost half (~45%) of their user requirements. Although we did not evaluate the validity of the user requirements that teams generated, previous studies have shown that novice designers who do not interact directly with users are more likely to make inaccurate assumptions about user needs [12,17,19]. As such, many of the user requirements that teams justified in terms of *Perceptions of user needs* may have been based on team assumptions rather than actual user needs, especially since few teams described validating their user requirements with additional user data in line with recommend practices [1,2].

Finally, 11 user requirements (13.1% of total), including revisions to previously reported user requirements, were included in team design reports without explicit justification. However, five of these *Unclear* user requirements represented changes made after Design Report 1 when teams were no longer incentivized to provide justifications for user requirements. Teams provided justifications for more than 90% of the user requirements that they identified in Design Report 1, in line with the expectations of the capstone course.

5.2 Justifications Provided by Novice Designers when Developing Engineering Specifications

Teams typically used different justifications for their engineering specifications compared to their user requirements; the three most common justifications for engineering specifications were *Sponsor interactions*, *Technical research*, and *Prior work*. Five teams reported that their project sponsors provided specific target values for certain design parameters (e.g., size) in their initial sponsor meetings. Similar to previous studies of novice designer behaviors [5,31], teams seem to have accepted these provided values as their engineering specifications with only limited further development.

Six teams used *Technical research* as a justification for at least one of their engineering specifications, in line with previous descriptions of capstone design team approaches to developing engineering specifications [6]. This justification seems to have been used in two main contexts. First, teams used the *Technical research* justification when they translated qualitative user and sponsor wants into quantitative values as part of Design Report 1. Second, teams used the *Technical research* justification when they revised their engineering specifications as part of their engineering analysis activities starting in Design Report 3.

Prior work was used as a justification for engineering specifications a large number of times overall but only by two teams (A and B). These two teams, along with Team C, were the only teams working on continuing capstone projects (i.e., some work had been completed the previous semester by another capstone design team [19]), which is likely why no other team used the *Prior work* justification. Team A in particular relied heavily on *Prior work* to justify their engineering specifications (66.7% of their total) and used these prior values as the main basis for their own work. It is also important to note that the *Prior work* code in our study was somewhat narrowly defined based on the data that emerged from this particular analysis; participating teams did not refer to benchmarking of existing products when justifying their user requirements and engineering specifications. Anecdotally, author-instructors of the course have previously noted substantial use of benchmarking to inform engineering specification development by other capstone teams. Future coding schemes should consider expanding the *Prior work* code to include benchmarking of existing and/or commercialized products, systems, or services.

Finally, 38 engineering specifications (approximately one third of the total), including revisions to previously reported engineering specifications, were included in team design reports without explicit justifications. This total is high given that justifications for engineering specifications were assessed (30% of grade) in Design Report 1. In many cases involving *Unclear* engineering specifications, teams provided justifications for their corresponding user requirements but did not justify how they translated those user requirements into quantified engineering specifications. While we did not gather data that would allow us to determine why teams did not clearly justify these engineering specifications, there are a few possible explanations. For example, some teams may have been unsure how to properly cite the information sources from which they drew their engineering specifications. Team E specifically may have experienced this challenge since almost all (~90%) of their engineering specifications had *Unclear* justifications. Another possible explanation is that teams may have been unsure how to justify changes or additions made to their engineering specifications as part of their verification and validation processes, since ten *Unclear* engineering specifications occurred in teams' final reports. Lastly, 17 out of 38 *Unclear* engineering specifications (including the 10 *Unclear* engineering specifications from team final reports) occurred after Design Report 1 when teams were no longer incentivized to provide justifications for engineering specifications. Teams might have provided justifications in these cases had they been required to do so, especially since teams did explicitly justify 17 other additions or revisions to engineering specifications that occurred after Design Report 1. More work is needed to understand how these potential challenges might variously impact novice designer processes when developing engineering specifications for their design projects.

5.3 Limitations

One limitation of our study was that we did not verify to what extent the user requirements and engineering specifications that teams justified in terms of *Sponsor interactions* and *User interactions* were grounded in stakeholder data. For example, some teams may have developed engineering specifications that they claimed were based on *Sponsor interactions* but in fact were drawn from other information sources. Another study limitation was that we only collected data from a subset of teams in a single semester of the capstone course; it is possible that teams in other capstone sections or working on other types of projects would have employed different approaches to justifying their user requirements and engineering specifications. A third study limitation was the relative lack of diversity across our participants, with 79.4% of participants identifying as White and 76.5% identifying as male. Finally, we did not collect data on the quality or appropriateness of the final prototypes that teams developed for their capstone course; as such, it is unclear what effects the user requirements and engineering specifications developed by each team had on their final solution quality.

5.4 Implications

In this preliminary study, we identified several ways that novice designers might justify the user requirements and engineering specifications that they develop for their projects. Our findings suggest that novice designer approaches to developing and revising user requirements are different from their approaches to developing and revising engineering specifications. Consequently, the specific challenges that novice designers may encounter when developing user requirements are likely different from the challenges they may encounter when developing engineering specifications. Our justification categories helped us characterize these various challenges as they emerged in the context of our study. In addition, our descriptions of the ways that capstone teams justified their user requirements and engineering specifications may be transferrable to other novice designer contexts as well.

Based on our findings, novice designers would likely benefit from additional tools and support to help them develop user requirements that are grounded in user data. One challenge that capstone teams may face is finding and accessing relevant users from whom to gather data [6,19]. While stakeholder mapping tools (e.g., [32]) may help capstone teams identify potential users, additional support may be needed to help capstone teams access these users and gather data effectively. Novice designers may also encounter additional difficulties synthesizing user data into user requirements and engineering specifications [6]. Some market-oriented tools and methodologies such as Kano modelling [1,2] and Quality Function Deployment [1–3] already exist to help designers develop and evaluate user requirements based on user data. However, novice designers may need tools that are specifically tailored to curricular design contexts.

Novice designers might also benefit from additional support to help them develop engineering specifications that are grounded in user data. Although *Sponsor interactions*, *Technical research*, and *Prior work* (including benchmarking) are all useful ways to develop engineering specifications, recommended practices suggest also validating engineering specifications with user data [1,3]. However, novice designers may encounter difficulties when quantifying user data to inform their engineering specifications [5,6]. Prototypes (especially low-fidelity physical models) represent one type of tool that can facilitate quantitative data collection by enabling users to interact with physical representations of different design parameters [15]. Previous studies indicate that prototypes may be underutilized by novice designers as a tool for developing engineering specifications [16]. Thus, design training could include guidance on how to leverage prototypes effectively for gathering quantitative data from users to aid in the translation of user requirements into engineering specifications and to validate engineering specifications.

6. CONCLUSION

Our study explored how novice designers justified the user requirements and engineering specifications that they developed as part of their capstone design projects. We identified a range of justifications provided by teams that may be transferable to other novice designer contexts. The extent to which each justification was used varied substantially across teams, and teams typically used different justifications in describing their user requirements compared to their engineering specifications. Furthermore, we found that while teams justified most of their user requirements, they did not provide explicit justifications for roughly one-third of the engineering specifications that they developed. Our findings suggest that novice designers may need additional support to help them develop user requirements and engineering specifications that accurately reflect user needs.

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