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An Investigation of Engineering Students' Information Sorting Approaches Using an Open-Ended Design Scenario

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An investigation of engineering students' information sorting approaches using an open-ended design scenario

Abstract
This education research and assessment paper describes a pilot study exploring how undergraduate engineering students sorted information related to an open-ended design scenario. To develop effective solutions, engineers must interpret design-relevant information from stakeholders, benchmarked products, and secondary research and synthesize this information into stakeholder needs and requirements. While literature has explored how engineering students gather design information, less work has explored how students make sense of this information. To understand how engineering students may approach information synthesis tasks, we provided ten undergraduate engineering students with 25 pieces of information related to an open-ended design scenario – designing a campus study space – and asked participants to sort this information based on perceived relevance to the scenario. We also asked participants to sort information they identified as clearly relevant into categories of their choosing. Participants consistently sorted eight of our 25 pieces of information as either "possibly relevant" or "not relevant" because they felt this information: did not relate to their main stakeholder (other undergraduate students); did not affect the physical layout of the study space; or did not affect their current design process. Participants' approaches to categorizing clearly relevant information resembled either "primary dimension sorting," where categorization was based on a single major dimension of difference, or "family resemblance sorting," where participants created multiple interrelated categories that preserved information diversity. Students and instructors may use our findings to support reflection on students' information sorting approaches and to encourage comprehensive practices for making sense of diverse stakeholder and contextual information.

Keywords: design problem scoping; information processing; design stakeholders; design scenario; undergraduate engineering students

1. Introduction

Engineering design problems are inherently open-ended; as a result, engineers rarely start with all the necessary information required to understand stakeholder requirements and develop appropriate solutions [1], [2]. Design-relevant information can come from many sources, including but not limited to interviews and observations with design stakeholders, research into existing products, codes and standards, and secondary research on the design context [3], [4], [5], [6]. Effective engineering designers sift through information from diverse sources and synthesize key insights that enable them to predict the impacts of their solutions and develop relevant criteria for solution evaluation [2], [4], [6]. These information gathering and synthesis processes are crucial to designing solutions "that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" [7].

However, while information gathering and synthesis skills are crucial to effective engineering design practice, content related to these skills is rarely included in standard engineering curricula [8]. To address this educational gap, prior work has largely explored how engineering students gather information for their design projects. This prior research has identified challenges that engineering students may encounter with gathering information [9], [10], [11], [12], effective practices that engineering students may use to gather information [9], [11], [13], and opportunities to pedagogically support engineering students in gathering information [14]. Limited research has explored how engineering students subsequently synthesize or make sense of the information that they have gathered. Studies of capstone engineering students have identified several challenges encountered by students related to their information synthesis processes, such as difficulties navigating contradictory stakeholder information [10], [15], limited incorporation of environmental, economic, or socio-cultural considerations [15], and the development of user requirements that are insufficiently grounded in user data [3]. Detailed descriptions of how engineering students make sense of design information are needed to clarify the sources of these reported challenges and develop engineering design pedagogies that support engineering students in effectively gathering and applying design information to their projects.

As a first step in gathering detailed descriptions of engineering students' information synthesis processes, this preliminary study investigated how engineering students categorized information related to a simulated open-ended design scenario: designing a campus study space. Our goal was to elicit details on how students determined information relevancy and organized information that they deemed relevant to design work. By providing students with information, we also sought to reveal student challenges or approaches that may be unique to information synthesis, i.e., that may emerge regardless of the quality of students' information gathering.

2. Background

2.1 Engineering student use of stakeholder and contextual information to inform design projects

Research has described several areas where engineering students may encounter challenges related to gathering and synthesizing stakeholder and contextual information to inform their design projects. Broadly, these challenges fall into four areas: 1) planning information gathering, 2) locating information and evaluating information quality, 3) processing and interpreting information, and 4) applying information to design decisions. The first two areas represent challenges with information gathering [9], [12], [13], whereas the last two areas represent challenges with information synthesis [16], [17].

Related to planning information gathering, student teams that lack prior familiarity with their intended stakeholders may struggle to develop a detailed plan in advance for gathering project-relevant information [18]. Student mindsets regarding the value of stakeholder input can also affect their plans for information gathering. For example, Zoltowski et al. [19] explored how 33 engineering student designers experienced designing for others. In their findings, they described an outcome space ranging from "technology-centered design," with limited consideration of stakeholders, to "empathic design" involving deep engagement with stakeholders. Other studies [9], [20], [21] have found that engineering students' impressions of the value of stakeholder information directly inform their willingness to gather and apply stakeholder information.

Research (e.g., [22], [23]) has also found that engineering students struggle to consider the broader context of their work beyond technical considerations. While studies vary in how they define "broader context," they consistently emphasize that engineers should look beyond technical functionality to consider political, environmental, and cultural contexts that could impact or be impacted by a project. For example, Mazzurco and Daniel [23] analyzed 26 engineering students and 16 engineering practitioners' responses to a design task. They found that students and practitioners were both able to provide high-quality considerations related to technology, but students struggled with considerations related to stakeholders and local norms, laws and ethics, and other socio-material contexts. A “culture of disengagement” in engineering education may also lead students to view broader context as irrelevant to engineering work [24], [25], and students may neglect to gather information on broader context as a result.

Even when students are motivated to gather a wide variety of information, they may still struggle to locate information and evaluate information quality. For example, Wertz et al. [12] analyzed memos submitted by first year engineering students that documented their evidence-based justifications for a design solution. They found that students overwhelmingly relied on web sources and that over half of these sources were either written for a popular (as opposed to scholarly) audience and/or were not strictly informational. Other studies have described students struggling to locate relevant stakeholder information online [18], [26] or struggling to find a stakeholder who could provide needed information within course time constraints [10], [27]. When meeting with stakeholders, students may also struggle to solicit information effectively, for instance because they ask closed-ended questions or use overly technical language [10], [13].

At the end of information synthesis, students may struggle to apply stakeholder and contextual information to inform their design decisions. At a basic level, Wertz et al. [12] and Loweth et al. [3] have described issues where first year and capstone engineering students, respectively, may fail to properly document their sources in their design deliverables. In such cases, students’ use of stakeholder and contextual information can be hard to evaluate properly. In terms of contextual information use, Burleson et al. [15] investigated how 20 capstone design teams incorporated contextual factors or “characteristics of a potential solution’s broad use-context” into their design work. They found that teams working on international projects and/or projects that were slated for immediate implementation tended to emphasize contextual factors more in their work. They also found that teams incorporated quantitative information more consistently than qualitative information. In a study of two engineering programs that focused on public welfare, Niles et al. [28] found that engineering students struggled to incorporate stakeholder perspectives into their work, particularly when these perspectives conflicted with their own.

While prior studies have described how engineering students gather, locate, evaluate, and apply information, less work has explored how engineering students process or interpret gathered information. Prior work on this aspect of information synthesis has primarily focused on student difficulties navigating conflicting stakeholder perspectives [10], [11], [13]. The processing and interpreting of gathered information is a crucial part of inductive qualitative analysis processes [29], [30], [31] – such as those that engineers use to define their design problems and formulate user requirements [3], [4], [32] – that directly impacts how students apply information. For example, if students are unable to make sense of information that they gather from stakeholders, then it is unlikely that they will use such information in their projects [10]. Challenges with making sense of qualitative stakeholder and contextual information certainly relate to student challenges with planning information gathering and locating information sources. However, there may be additional challenges that are specific to processing information that have thus far been underexplored. These additional challenges could relate to other documented student designer behaviors, such as discomfort with design ambiguity [9], [33], prioritization of engineering domain expert perspectives over stakeholder perspectives [9], [11], and emphasis on technical considerations over broader context considerations [15], [22].

2.2 Inductive categorization of qualitative data in engineering

Inductive qualitative analyses include several interim steps of sense-making wherein researchers translate raw data into reportable insights. For example, thematic analysis, which is one type of inductive qualitative analysis approach, typically involves the following steps [31], [34]:

1. Identify interesting features of gathered data points.
2. Categorize data based on these features.
3. Review categorizations to ensure that they are internally consistent.
4. Name and define categorizations as "themes" that answer research questions.
5. Repeat previous steps as needed.

Crucially, the outcomes of thematic analysis rely on the outcomes of the researchers' initial categorization of the data. This subjectivity is embraced in qualitative research [34], [35]; however, new researchers require training to navigate this subjectivity effectively [36]. Unfortunately, training on qualitative synthesis processes is rarely included in standard engineering curricula.

In order to develop effective pedagogy that supports engineering students in applying qualitative analysis methods to interpret stakeholder and contextual information, we must first understand how engineering students may approach qualitative categorization tasks by default. Research in this area thus far has been limited, although one closely related study by Damen and Toh [37] explored how four expert software engineers organized information related to an idea generation task. The authors found that their participants employed approaches to information sorting that were similar across participants, although the outcomes of these approaches differed. They also found that their participants iterated on their information categories as they encountered new information, evaluated information based on how it impacted the project, and applied prior knowledge to inform their sorting approach.

Beyond engineering, research in the field of psychology has explored the mental processes behind categorization tasks. Researchers have identified two main categorization schemas: "primary dimension sorting" and "family resemblance sorting." In primary dimension sorting, individuals sort unfamiliar items (such as objects, pictures, or information) into two or more categories based on one clear dimension of difference [38], [39]. Primary dimension sorting minimizes between-group overlap, meaning that the resulting groups are as distinct as possible. However, if items feature multiple dimensions of difference, then primary dimension sorting can also result in significant within-group variation (i.e., high levels of difference between items in the same group) [38], [39]. By comparison, in family resemblance sorting, individuals sort unfamiliar items into interrelated categories that preserve as much of the overall item diversity as possible [38], [39], [40]. In other words, the goal of family resemblance sorting is to capture multiple dimensions of difference that may exist across items while still forming coherent groups that emphasize similarities between items. [38], [40]. Ultimately, these two categorization schemas represent points on a spectrum; individuals' actual sorting approaches may exhibit characteristics that blend primary dimension and family resemblance sorting. However, of these two sorting approaches, family resemblance sorting more closely resembles the cognitive process that is encouraged in inductive qualitative analyses. Without prior training, it is unclear whether engineering students' information sorting approaches are more likely to resemble primary dimension sorting or family resemblance sorting. It is equally unclear what implications these different sorting approaches may have for engineering students' design processes.

3. Methods

3.1 Research questions

This study represents a first step towards understanding how engineering students process design information, decoupled from students' potential challenges with information gathering. Within the overarching topic of information processing, we particularly focused on how participants categorized information for a design task. We sought to answer the following research questions:

RQ1. How do undergraduate engineering students determine information relevance for an open-ended design scenario?

RQ2. How do engineering students organize information that they have already determined is "clearly relevant?"

3.2 Scenario development and study design

This study employed a simulated, open-ended design scenario to explore how engineering students categorized information. Open-ended design scenarios have been previously used to observe how engineering students scope engineering problems [41], interview stakeholders [14], and develop solutions [42]. We used a scenario approach to answer our research questions because we sought to observe the immediate outcomes of students' information categorization approaches while also controlling the information inputs to these approaches. We created the following design scenario for use in this study:

[Midwest University] has hired you as an engineering consultant to design a study space on campus for undergraduate engineering students. As the university continually strives to enhance the learning environment for students, there is a growing need for a dedicated area that facilitates effective studying and promotes academic success. To help you with your problem definition work, [Midwest University] hired a firm to conduct background research related to the proposed study space. The firm prepared the following dossier of information and insights. However, they intentionally did not filter this information for relevance, preferring to leave that up to your judgment as an engineer.

We intentionally designed this scenario to be accessible to undergraduate engineering students regardless of major or year of study. We scoped our scenario based on a playground design scenario that has been used in previous design research studies ([41], [42], [43], [44]).

Along with this design prompt, we prepared 25 pieces of information related to the scenario. We considered three main dimensions while creating our information: **stakeholders**, **data type**, and **contextual categories.** These dimensions were for internal organization and were not shared with participants. "Stakeholders" included considerations relating to direct stakeholders – i.e., individuals who directly interact with the solution [45] – and indirect stakeholders – i.e., individuals who may not directly interact with the solution but are still affected [45]. "Data types" included considerations related to how the information was gathered. "Contextual categories" referred to use context considerations that could influence the solution's design and implementation, such as described in [15], [22], [46]. We focused on these three dimensions based on prior research suggesting that engineering students may consider indirect stakeholders [19], [20] and "non-technical" contextual information [15], [25] to be beyond the scope of their engineering work and may struggle to interpret data from qualitative versus quantitative sources

[10], [15]. Table 1 provides examples of how we implemented these three dimensions while creating our 25 information. The full list of 25 pieces of information is included in the Appendix.

Table 1. Dimensions used to construct scenario information.

Dimension	Varieties Included	Example Information
Stakeholders	Direct: Undergraduate engineering students Indirect: The university; maintenance staff; student organizations; professors; donors; industry partners; local residents	"The [University student newspaper] conducted short interviews **with professors** about their thoughts on the new study space. Two-thirds of interviewed professors indicated that they would prefer for the study space to be mixed-use so that it could also function as a classroom."
Data types	Surveys; observations; interviews; internal university reviews; expert research	"**Observations of classrooms** revealed that students often need charging ports for at least one device (laptop or tablet) to engage effectively in their studies."
Contextual categories	Diversity, equity, and inclusion; supply chain logistics; laws and regulations; COVID-19; safety; sustainability; time scale; technology needs; educational needs; budget	"Government regulations are increasingly requiring the use of reusable and recyclable building materials to **promote sustainability and reduce environmental impact**."

3.3 Participants

Data were collected from ten undergraduate engineering students participating in a summer research experience at a large Midwestern University. Table 2 provides aggregate academic information for participants.

Table 2. Aggregate academic information for participants (n_{total} = 10).

Type of academic information	Participant characteristics
Year of Study	3 seniors; 4 juniors; 3 sophomores
Engineering Major	5 mechanical; 2 chemical; 2 electrical; 1 aerospace

Our sample size of ten participants was informed by two considerations. First, this pilot study represented a limited test of the efficacy of our scenario methodology before scaling up to a larger study. Second, our sample size of ten participants enabled us to devote individual attention to the interviews and sorting processes of each participant to uncover nuances in how each participant worked through our scenario. A sample size of ten participants is also in keeping with similar studies of how engineering students [47] and practitioners [37] process information for open-ended design tasks.

3.4 Data collection

Each participant participated in a 30-minute information sorting task followed by a 30-minute interview. The first and second authors collaboratively interviewed all ten participants. During the information sorting task, participants were presented with the study space design scenario and 25 pieces of information. The scenario was introduced, and participants were asked to sort the information into three piles: “clearly relevant,” “possibly relevant,” and “not relevant.” The researchers communicated to participants that “clearly relevant” meant the information definitely needed to be accounted for by engineers to develop an effective solution; “possibly relevant” information might or might not be useful to an engineers’ work; and “not relevant” information was unrelated to an engineers’ work in the scenario and was thus unnecessary to consider further.

Once participants finished their initial sorting, they were instructed to further sort their pile of “clearly relevant” information into categories based on topic. Interviewers suggested “criteria and constraints” as one sorting example but clarified that any sorting approach was valid because the research goal was to see how students identified links between the provided information. Participants had a total of 30 minutes to complete both sorting tasks (information relevance and organization of relevant information), during which the interviewers waited in a separate room. At the conclusion of the sorting tasks, the interviewers photographed each participant’s final sorting arrangement. We did not ask participants to think aloud during their sorting tasks.

Following the sorting tasks, the researchers conducted a 30-minute semi-structured interview with each participant. The semi-structured interview format allowed the researchers to systematically explore participants’ thought processes related to their information sorting tasks while also providing flexibility for the researchers to probe interesting responses for deeper insight. Interview questions included:

- For each information you sorted as “not relevant,” could you tell me more about why you felt this information was not relevant?
- For each information you sorted as “possibly relevant,” could you tell me more about why you felt this information was possibly relevant?
- For your clearly relevant information, what is the topic for each group?
- How did you decide on these topics?
- For each topic, tell me how you feel that it is relevant to your work as an engineer.
- Was there any information that you moved between piles as you worked? In other words, any information that became more or less relevant or moved between clearly relevant groups?

Post-task interviews were transcribed to facilitate data analysis.

3.5 Data analysis

To answer RQ1, we first counted how many times each of our 25 pieces of information was sorted as “clearly relevant,” “possibly relevant,” and “not relevant.” We then identified information that was sorted by more than half of our participants in total as “possibly relevant” or “not relevant.” In interviews, we asked participants to provide rationales for each piece of information that they sorted as “possibly relevant” or “not relevant.” We collected these rationales for each piece of information from participant transcripts. Authors 1 and 2 then reviewed the rationales for each information and identified rationales that recurred across participants for sorting a given piece of information as “possibly relevant” or “not relevant.”

To answer RQ2, we initially planned to employ an inductive categorization process to describe different ways that participants sorted their “clearly relevant” information. However, upon reviewing our data and conducting initial analyses, we found that participants’ sorting approaches seemed to generally align with primary dimension and family resemblance sorting schemas. Thus, we ultimately categorized our participants deductively based on these two sorting schemas described in our background section. We categorized participants' approaches as primary dimension sorting if their interview explanations for their sorting approaches emphasized one major discernable dimension of difference. We categorized participants' approaches as family resemblance sorting if their interview explanations described the formation of multiple interrelated categories that lacked a single discernable dimension of difference.

4. Findings

4.1 RQ1: Participant rationales for sorting information as "possibly relevant" or "not relevant"

Out of the 25 pieces of information provided to participants, 17 were selected by at least half of our participants as clearly relevant to the design of the study space. The remaining eight pieces of information are shown in Table 3. This table includes information on how many participants selected each information as "possibly relevant" or "not relevant" and summarizes the reasons that participants did not sort this information as "clearly relevant."

Table 3. Information identified by participants as "possibly relevant (PR)" or "not relevant (NR)." Frequency "n" is out of 10 participants. Information is ordered by NR frequency.

Information	*"PR" n*	*"NR" n*	Main Reason
[Local] high schools seek to collaborate with [University] and offer high school students the chance to immerse themselves in the university atmosphere and take advantage of the study spaces provided by [University]. This collaboration aims to cultivate a conducive learning environment, foster community engagement, and establish a smooth educational transition between high school and college.	3	5	[Local] high school students are not the direct user; Limited impact on the physical layout of the study space
Internal budget analyses indicate that [University] will need to raise undergraduate tuition by $2 to fund the study space maintenance.	1	5	$2 is too small to be considered
[University]'s preferred furniture supplier says that desks and chairs for the study space are on 6-month backorder.	1	5	Limited impact on the physical layout of the study space
Student organizations, including sororities and fraternities, have requested that the study space be reservable for events.	4	3	Student orgs are not the direct user
[University] estimates they will go through a redesign process for this study space in 15 years.	4	3	Limited impact on current design process
For the past five years a coalition of [Local] residents have been advocating for [University] to spend more money locally when purchasing materials and labor for campus projects.	4	3	Limited impact on the physical layout of the study space

Industry partners are eager to utilize the study space as a platform for promoting internships, job opportunities, and other initiatives.	7	0	Industry partners are not the direct user
To foster connections with undergraduate students and expand their professional networks, alumni want to organize weekly networking gatherings in the study space and hope this initiative provides a platform for alumni and undergraduate students to share insights, build relationships, and explore professional opportunities.	7	0	Alumni are not the direct user

In sorting information as "possibly relevant" or "not relevant" compared to "clearly relevant", one common rationale provided by participants was that the *information did not pertain to the direct user of the study space*. For the study space scenario, participants consistently defined the direct user as other undergraduate students. For example, eight participants (3 PR, 5 NR) indicated that the information "[Local] high schools seek to collaborate with [University]..." was less than clearly relevant because participants felt that [Local] high schools were not a critical stakeholder group. As described by one participant who sorted this information as "not relevant:"

"This could be relevant, but… I guess all of these are dealing with like, external wants. Not really immediately relevant to what the student wants and what the student needs in the classroom." (Participant 8, not relevant)

Similarly, information relating to industry partners (7 PR), alumni (7 PR), and student organizations (4 PR, 3 NR) were also frequently selected by participants as being less than clearly relevant. For instance, in the words of one participant who sorted the information on industry partners as "possible relevant:"

"I was thinking that [industry partners] can be relevant because promoting internships, jobs, and other initiatives can promote academic success, but I feel that in a study space, it should be clearly for studying and getting work done... So I didn't feel [that information] was really necessary in that space, but it does have applications... in facilitating academic success." *(*Participant 10, possibly relevant*)*

Participants also sorted information as "possibly relevant" or "not relevant" if the information, in their evaluation, *had limited impact on the physical layout of the study space*. For example, seven participants (4 PR, 3 NR) indicated that the information "For the past five years a coalition of [local] residents have been advocating…" was not "clearly relevant." Participant rationales related to this information centered around how the information should be a secondary consideration that engineers baddress after the physical design (i.e., the layout) of the study space had been determined. For instance:

"I think again, it's like an issue of priority. Like of course, if we were to like find a cost-effective way of using local materials and labor, I'm all for it. I think that should be good for the design, but I don't think that should be the center of the design. You know, it's a study space and not

really like a testament to [Local] materials and whatnot. So, I think it would be nice to have if there was a cost-effective option." (Participant 2, possibly relevant)

Six participants (1 PR, 5 NR) provided a similar rationale to justify why the information "[University]'s preferred furniture supplier…" was less than clearly relevant. While [University]'s preferences were important, participants felt that the furniture issue was not "clearly relevant" because it did not directly impact the design of the study space. As described by one participant who felt this information was not relevant:

"There isn't much that can be done to reduce the six month [backorder]. There's not much you can do about this as an engineer, so we're gonna put it in 'not relevant' because also you can design [the space] and not take [this information] into account because [the space] is not changing anyway. [The information] doesn't super impact your process." (Participant 4, not relevant)

In other words, Participant 4 felt that an engineering designer working in this space could figure out the physical design of the study space first, and then afterwards clarify the needed furniture.

As a third rationale, participants also sorted information as "possibly relevant" or "not relevant" if the information, in their evaluation, *had limited impact on their current design process*. This rationale applied to the information "[University] estimates they will go through a redesign process…," which was selected by four participants as "possibly relevant" and three participants as "not relevant" because of the fifteen-year time horizon. As described by one participant who selected this information as "possibly relevant:"

"The thing was the 15 years duration of it. If it were a smaller duration, I would put [that information] in the 'clearly relevant' pile. Since it's a design process that's going to [happen] in the span of 15 years, it is important to take that into account as a constraint in designing a study space. But then again, because it's such a long period of time, it's not really that relevant to consider right now." (Participant 10, possibly relevant)

In other words, the fifteen-year redesign was far enough in the future that Participant 10 felt they did not have to worry about this information "right now" while designing the study space.

Lastly, and unrelated to the above three justifications, six out of 10 participants (1 PR, 5 NR) indicated that the information "Internal budget analyses indicate…" was less than clearly relevant. Participants indicated that the impacts associated with this information were too small to matter. In the words of one participant:

"$2 as a student wouldn't be a big deal to me and [the information] doesn't say anything about how changing the design of the space would change anything about that." (Participant 9, not relevant)

4.2 RQ2: Participant approaches to organizing "clearly relevant" information

While participants generally agreed about which information was clearly relevant, we observed limited consistency in how participants grouped clearly relevant information (i.e., every participant formed groups with different topics containing different information). However, looking at participants' sorting approaches holistically, we found evidence of both primary dimension sorting and family resemblance sorting. Participants' sorting approaches tended to resemble one or the other sorting approach. We also observed two different sorting approaches that exhibited primary dimension sorting characteristics.

4.2.1 Primary dimension sorting A: Initial binary groups

Four participants used sorting approaches that resembled primary dimension sorting, i.e., they formed groups that reflected a single major discernable dimension of difference and/or minimized between-group overlap. Two of these participants formed binary categories, one of which they further divided into sub-categories. For example, Participant 9 divided information into "Physical layout" and "Non-layout" groups, and then further divided their "Non-layout" group into "Physical objects", "Relevant info", and "Aesthetics" groups. As they described:

"I decided on the groups after reading all the cards. This ["Physical layout" group] came together because, like, for me thinking visually, the layout of the space is a very primary thing to have, and all [this information in the group] dictates how it needs to be laid out. How, you know, do you want to have cubbies or if you want couches or if you want tables, that kind of stuff. None of the rest of these [information] directly tied in with that." (Participant 9)

In this case, relevance to the physical layout of the study space was Participant 9's primary dimension of difference. Participant 9 used this sorting approach because, from their perspective, defining the physical layout of the study space was a priority. The information in their "Physical objects," "Relevant info" and "Aesthetics" categories could be accounted for after the layout had been set. The relationship of Participant 9's information categories to the overall design task is depicted in Figure 1. The other participant that used an "initial binary groups" sorting approach (Participant 5) created a "Physical characteristics of the space" group than contained over half of their "clearly relevant" information and then divided remaining "non-physical" information into "Budget," "Maintenance," "Room functions," and "Purpose of the space" groups.

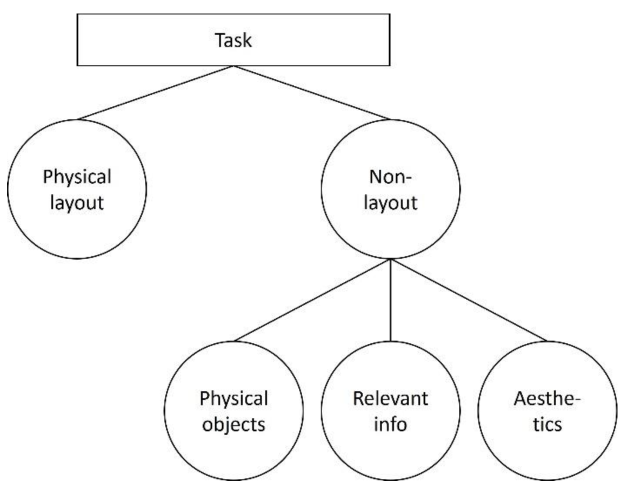

Figure 1. Participant 9 categorization scheme

4.2.2 Primary dimension sorting B: Two overarching groups

Two participants stopped at forming two information groups. The two groups formed by each of these participants were not oppositional, as in the example of Participant 9. However, participants still similarly tried to minimize between-group overlap as much as could reasonably be achieved given the complexity of provided information, which is a characteristic of primary dimension sorting approaches. Thus, we categorized these two participants' approaches as primary dimension sorting as well.

As an example, Participant 3 sorted their clearly relevant information into "effectiveness" and "promotes academic success" based on their interpretation of the design prompt. In their words: "*This goes back to how I was given two tasks: making [the space] effective and making it promote academic success. That is how I differentiated these two [groups]*."

Participant 3 sorted all their clearly relevant information into one of these two groupings and did not further account for the diversity of information contained within their two groups. The relationship of Participant 3's information categories to the overall design task is depicted in Figure 2. The other participant that used a "two overarching groups" approach (Participant 6) sorted their information into "objectives" and "constraints" groups and interpreted the information contained in each group as standalone objectives and constraints.

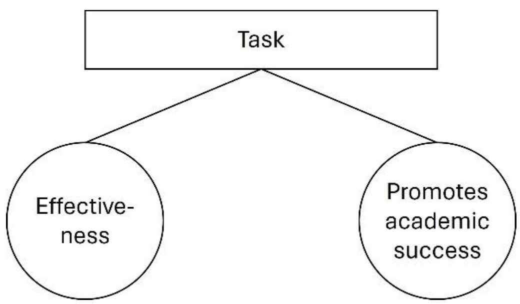

Figure 2. Participant 3 categorization scheme

4.2.3 Family resemblance sorting

Six participants used sorting approaches that more closely resembled family resemblance sorting, i.e., they constructed several distinct categories of information that 1) reflected interrelationships between information as it pertained to the study space and 2) preserved some of the diversity of provided information in terms of stakeholders, data types, and contextual categories. As one example, Participant 2 created five information groups: "budget," "dynamic of the study space," "student comfort," "physical accessibility," and "security." As they described:

"I thought, like, 'what are the main priorities?' When I'm just beginning this design, analysis, everything's about money in the end, so of course, 'budget' is a priority. That's the first group I made. Secondly, of course, students want a study space that really parallels with their own study habits. So it's definitely a priority that students will actually like the study space that they're in. And then to kind of bounce off of that students want to feel comfortable, and they want to use this study space for a long time. Moreover, the university wants to attract as many students as possible to the study space. So overall, student comfort is also a priority. And then lastly, of course, that the building has to be very accessible not just because [University] wants to attract students from diverse backgrounds, but it needs to be a safe building. And then in tandem with

that, it has to be a secure building. Just you know, obviously for security risks. Students want to feel comfortable, not just because of comfy furniture and like a pleasing area, but also they want to feel comfortable in that their stuff doesn't get stolen. So I just I thought along like the priorities as an engineer like cost and the priorities of the student comfortability… and then a plan for like a study space would want to reflect those priorities." (Participant 2)

In other words, Participant 2 identified these five groups by thinking about the priorities they should attend to as an engineering designer. In describing their categories, Participant 2 also discussed stakeholder considerations related to both students and the university. The relationship of Participant 2's information categories to the overall design task is depicted in Figure 3. Compared to the primary dimension sorting approaches described above, Participant 2's sorting approach does not reflect a single dimension of difference; rather, the categories are interrelated and have equivalent relationships to the main design task.

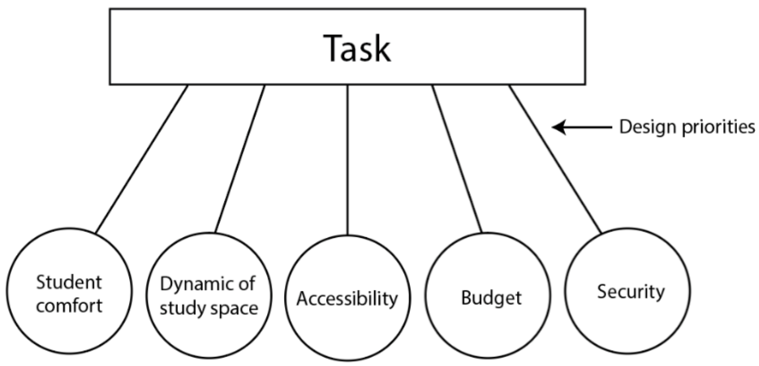

Figure 3. Participant 2 categorization scheme

Participant 8 also used an approach with characteristics of family resemblance sorting. Like Participant 2, Participant 8 also created five groups: "Requirements by University and Government," "Budget," "Information Related to Students but not from Students," "University/Alumni Wants," and "Students Wants." Participant 8 created their groups by categorizing their information as it related to the design task. As they described:

"So [this group is] all requirements. This [group] is all direct information from the students through surveys and interviews… this [group] is useful information that isn't from the students that I think would be very important to consider when designing a space. This [group] is just the budget constraint… And then this ["University/Alumni wants" group] is everything else, like important stuff that doesn't really fall into any of these other categories." (Participant 8)

In other words, Participant 8 looked for similarities in the provided information to form groups. Each category served a purpose in organizing information and relating this information back to the design task. Participant 8's categories also reflected the diversity in the provided information by emphasizing different stakeholders and different information sources. The relationship of Participant 8's information categories to the overall design task is depicted in Figure 4.

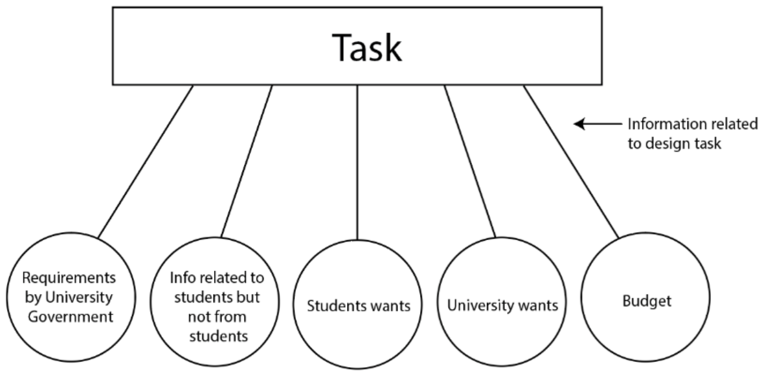

Figure 4. Participant 8 categorization scheme

5. Discussion

5.1 RQ1: Participant rationales for sorting information as "possibly relevant" or "not relevant"

In summary, our participants determined information relevance in several ways. One method involved identifying a central stakeholder: other undergraduate students. Participants frequently sorted information that was related to non-student stakeholders, such as faculty, alumni, and high school students, as "possibly relevant" or "not relevant." In addition, participants also sorted information as "possibly relevant" or "not relevant" if they felt the information had limited impact on the physical layout of the study space or on their current design process.

Related to stakeholders, there are two clear observations from our data. First, our participants considered some stakeholders – namely, other undergraduate students – to be clearly relevant to their engineering work in the context of this simulated design task. This finding was encouraging because some prior studies, particularly related to the "culture of disengagement" in engineering education have shown that engineering students may not consider any stakeholder considerations to be relevant to their engineering work [24]. Our second observation was that participants designated some stakeholders as more important to their engineering work than others. Literature suggests that engineers should consider multiple stakeholder perspectives to develop effective engineering solutions [9], [18], and prior work has largely investigated the extent to which engineering students can identify multiple perspectives [48]. However, engineers must also make informed judgments about how to evaluate and prioritize information from stakeholders. Our findings provide examples of how engineering students may perform such judgements in the absence of specific training on working with qualitative data.

There are at least two potential reasons that our participants indicated that other university students were the most important stakeholders for the design of the study space. First, our participants may have found it easiest to focus on stakeholders that resembled themselves. Fila et al. [49], in a study of how engineering students utilized empathy in a non-immersive design task, found that their participants relied most on their own experiences (rather than the experiences of other potential users) to inform their designs. Our findings could reflect a similar student approach in the context of problem scoping. Another possibility is that participants leveraged experiential knowledge about study spaces on campus to identify other undergraduate students as direct stakeholders and chose to prioritize direct stakeholder perspectives over those of indirect stakeholders. We intentionally designed our study space scenario so that participants could make informed judgments about our provided information based on their own experiences. While prioritizing direct stakeholders is not necessarily a problem, it could become a problem if students subsequently ignore indirect stakeholders. It is unclear from this study if students would eventually use “possibly relevant” information, and thus return to other stakeholders, if they were working on a “real” design project.

Participants prioritized information as “clearly relevant” if they felt it impacted the design of the study space layout. Information such as using local materials was considered a “nice to have,” provided that the layout could be settled first. It is unclear how participants determined that some information did not significantly impact the physical layout of the study space, although anecdotally participants referred to their personal experiences with study spaces or their personal interpretations of the information (i.e., whether the information explicitly mentioned the study space layout). Our findings seem analogous to observations from Kilgore et al. [41]. This earlier study explored how first year engineering students scoped a design problem related to flooding of the Mississippi River and found that technical and logistical details of the flood wall dominated their participants’ responses as compared to details about the river water, riverbank, or surroundings. Similarly, Burleson et al. [15], in their study of capstone mechanical engineering students, found that their participants more readily integrated technological and institutional information into their projects than socio-economic factors. Thus, it is possible that our participants’ prioritization of layout information over non-layout information represents a novice design practice. As with stakeholders, it is unclear if students would eventually use “possibly relevant” information, and thus incorporate non-layout considerations, if they were working on a “real” design project.

We provided a single piece of information to participants that clearly communicated temporal considerations: “[University] estimates they will go through a redesign process for this study space in 15 years.” Only three of our ten participants felt that this information was clearly relevant; the remaining seven participants cited the time scale as a reason for downgrading the information to possibly or not relevant. There is limited prior work investigating how engineering students account for temporal considerations in their design projects. Dugan et al. [22], in their study of how engineering students and practitioners approach complex problem-solving, overall found that the consideration of temporal aspects of engineering work was limited across their participants. Our preliminary findings align with these earlier observations.

5.2 RQ2: Participant approaches to organizing “clearly relevant” information

We observed characteristics of primary dimension sorting and family resemblance sorting across our participants’ approaches. We did not give participants explicit instruction on how to organize clearly relevant information, although we did suggest criteria and constraints as one example sorting approach. Our pilot findings suggest that, in the absence of explicit sorting instructions, some engineering students may organize information according to a highly salient dimension of difference (i.e., primary dimension sorting), while other students may form multiple interrelated information groups that emphasize information diversity (i.e., family resemblance sorting).

We did not evaluate the effectiveness of a given sorting approach. However, our data do suggest possible negative implications of utilizing a primary dimension sorting approach to initially organize information during problem scoping. One implication is that students may prematurely condense diverse information through primary dimension sorting. For example, Participant 3 formed two overarching groups that related to user needs and requirements: “Effectiveness of the study space” and “Promotion of academic success.” It is unclear how Participant 3 would subsequently apply these groups to inform their design work. For example, would Participant 3 simply apply these two groups as overarching considerations, or would they eventually utilize the diversity of information contained within each group? In the former case, would the diversity of information still be retained in Participant 3’s design documentation? We lack answers to these questions, although previously reported engineering student challenges related to documenting information [3], [12] suggest a likely negative response to this last question.

A related implication is that students may miss important user requirements through primary dimension sorting. For example, Participant 9’s “Physical layout” umbrella group contained diverse information that could have been sub-grouped. In later stages of information synthesis, Participant 9’s “Physical objects,” “Relevant info” and “Aesthetics” groups seem likely to evolve into design requirements – this is a potential advantage of Participant 9’s sorting approach compared to the approach of Participant 3. However, it is still unclear how Participant 9’s “Physical layout” group would evolve. Participant 9 might transform this group into multiple physical layout requirements, treat the group as a single requirement, or perhaps incorporate information in this group into their overall problem statement. The risk again, given reported issues with documenting information [3], [12], is that Participant 9 may report “Physical layout” as a group and fail to retain information contained within the group for further synthesis. We do not have evidence that Participants 2 or 8, who used a family resemblance sorting approach, would do a better job than Participants 3 or 9 of using diverse information to inform their work. However, the family resemblance sorting arrangements of Participants 2 and 8 seem likely to facilitate the inclusion of diverse information in future steps of information synthesis, or at least more likely to avoid the potential documentation issues outlined above.

5.3 Limitations

As a pilot study, this research is subject to several limitations. First, there may be other ways that engineering students determine information relevance or organize clearly relevant information that were not observed in this study due to the small sample size. Participants’ sorting approaches could also be impacted by their major, year of study, co-curricular experiences, or personal identities. None of these potential explanatory factors was explored in this study. Our findings also do not provide information about what sorting approaches may be “typical” of engineering students. The inability to evaluate how participants would eventually use the provided information, beyond sorting based on intent, is another significant limitation.

Nine of our ten participants had experience developing “criteria and constraints” for an open-ended design problem in their first-year engineering design class. This prior experience may have influenced how these participants approached our design scenario. In the first step in our sorting task, we asked participants to form “clearly relevant,” “possibly relevant,” and “not relevant” piles. This instruction may have led participants to conclude that they must place at least one piece of information in each pile. Participants may also have placed more information in the “clearly relevant” pile than they would for a curricular or co-curricular design project, for instance because they felt that “clearly relevant” was the right answer or because they would not be bound to using their “clearly relevant” information in a “real” design.

Lastly, our scenario may have been too accessible to our participants. We achieved our goal in developing a scenario to which every participant could relate. However, participants' preconceived ideas about study spaces may have influenced their responses. In the future, a better approach would be to develop a scenario that is still accessible to students but lacks such a high degree of personal familiarity.

5.4 Implications

Our findings provide examples of how engineering students may sort design information in the absence of formal training in qualitative synthesis. Based on our findings, instructors who seek to support engineering students' information synthesis processes should provide explicit instruction on how to use information on indirect stakeholders and broader social context. Participants in our study often felt that such information was not "clearly relevant," and consequently it seems likely that our participants would struggle to apply such information to a "real" design project. One way to support students could be to leverage case studies of real world engineering projects – for example, drawn from Lucena et al. [50] or Trevelyan [51] – to demonstrate how engineers account for indirect stakeholders and broader social context in practice. Given the complexity of incorporating such information, engineering students would also likely benefit from individual mentorship from instructors that aligns with the ideas of cognitive apprenticeship [52]. Instructors could demonstrate how they would apply information on indirect stakeholders and broader social context for an example project and provide cognitive scaffolding to guide their students in mirroring their thought processes to make new connections for their own projects.

Instructors can also use our examples of primary dimension and family resemblance sorting to support students' reflections on how they process design-relevant information in preparation for future synthesis (e.g., into design requirements). For example, our findings show structurally different approaches to organizing design-relevant information; due to lack of experience, it is unlikely that engineering students would have previously considered that different approaches may exist. Once different organization approaches are introduced, students could identify advantages and disadvantages of the different approaches with respect to forming requirements. Students could then reflect on how they are organizing design-relevant information for a current project and identify advantages and disadvantages of their own approaches.

Design researchers could expand and iterate on our design scenario approach and pilot findings to deepen understandings of how engineering students process and interpret design information. We intentionally designed our scenario to be accessible to our student participants. However, this level of familiarity meant that students often leveraged implicit inferences to distinguish between "clearly relevant" and "possibly relevant" information, and the quality of these inferences was difficult to evaluate. Future iterations of this study could tweak the design scenario to focus on a topic and/or direct stakeholder group that has less overlap with participants. Additional possibilities include adjusting the 25 pieces of information to reflect different ways to categorize information (such as the "Source-Generality-Abstraction-Effectuation" dimensions from Damen & Toh [37]) and/or updating information to more clearly reflect dimensions of interest (such as temporality). Our design scenario approach could also be used to explore how prior experiences, such as participation in community-engaged co-curricular design projects, affect how engineering students determine information relevance and organize relevant information.

6. Conclusion

This study investigated how ten undergraduate engineering students sorted information related to an open-ended design scenario: designing a campus study space. We asked participants to first sort provided information based on perceived relevance to the design scenario, and then to sort clearly relevant information into categories. Of the 25 pieces of provided information, eight were consistently sorted by participants as either "possibly relevant" or "not relevant" because participants felt they: did not relate to the primary user (other undergraduate students); did not affect the physical layout of the study space; or did not affect current design processes. We observed limited consistency in how participants sorted clearly relevant information into categories, although we did observe evidence of two overarching categorization approaches: primary dimension sorting and family resemblance sorting. While we did not evaluate the effectiveness of these categorization approaches for problem-scoping, a potential drawback of a primary dimension sorting approach is that students may prematurely condense diverse information into reductive categories and miss important stakeholder needs or requirements as a result. Our examples of student information sorting approaches can be used by engineering students and design instructors to support reflection on how students make sense of potentially relevant design information. These sorting reflections can be a first step towards developing pedagogies that train students how to apply diverse stakeholder and contextual information to develop solutions that comprehensively address stakeholder needs and requirements.

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Appendix – Design Scenario and Information Provided to Participants

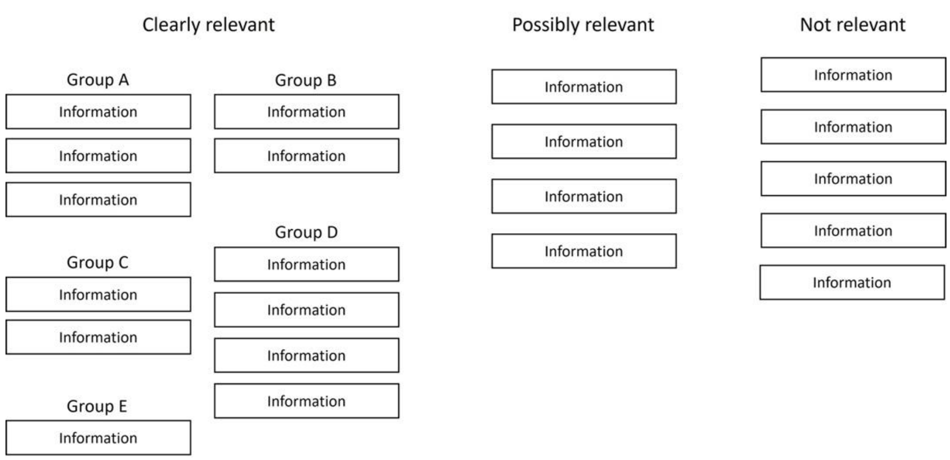
<u>Design Task</u>
[University] has hired you as an engineering consultant to design a study space on campus for undergraduate engineering students. As the university continually strives to enhance the learning environment for students, there is a growing need for a dedicated area that facilitates effective studying and promotes academic success. To help you with your problem definition work, [University] hired a firm to conduct background research related to the proposed study space. The firm prepared the following dossier of information and insights. However, they intentionally did not filter this information for relevance, preferring to leave that up to your judgment as an engineer.

<u>Instructions</u>
Step 1: Please sort the provided information into three piles as follow:

1. Information that you feel is **clearly relevant** to your work on the design task. In other words, as an engineer working on this project, you would definitely take this information into account to develop an effective solution.
2. Information that is **possibly relevant** to your work on the design task. In other words, as an engineer, you might use this information, or you might not.
3. Information that is **not relevant** to your work on the design task. In other words, information that, as an engineer, you don't think is related to the design problem or you think is unnecessary to consider further.

Step 2: Take the information in your **clearly relevant** pile and group this information into categories based on topic. Feel free to move information between your **clearly relevant**, **possibly relevant**, and **not relevant** piles as you work. Your final arrangement of information should look something like the following diagram.

You will have up to 30 minutes to complete this task, but you do not need to take the whole time. You also do not need to come up with any solutions, just sort the provided information.



Information (provided to participants on individual slips of paper and unnumbered)

1. [University] would like to use the space to demonstrate their commitment to diversity, for example by decorating the space with photographs or wall art reflecting their diverse student body.
2. A recent survey of undergraduate students indicated that 85% of students study in groups more often than they study alone.
3. [University]'s preferred furniture supplier says that desks and chairs for the study space are on 6-month backorder.
4. The American with Disabilities Act (ADA) mandates that public areas such as study spaces must be accessible for students with disabilities.
5. After the COVID-19 pandemic, [University] has required that face masks and hand sanitizer must be readily available and continuously stocked in any room with a potential occupancy of greater than 10 students.
6. According to prior research, it takes one maintenance staff approximately 1 hour to clean a 1000 sq.ft. space up to [University]'s standards for hygiene.
7. A recent survey of undergraduates showed that 60% preferred a space that several smaller study rooms that could fit up to 6 students, while 40% preferred an open study space. Subdividing the space would reduce the overall capacity of the space by 30%.
8. Observations of classrooms revealed that students often need charging ports for at least one device (laptop or tablet) to engage effectively in their studies.
9. Interviews with students suggest that one of the biggest annoyances with current study spaces is other students talking on their phones while other folks are trying to study.
10. [University] has provided a budget for the study space of $100,000.
11. Internal budget analyses indicate that [University] will need to raise undergraduate tuition by $2 to fund the study space maintenance.
12. Student organizations, including sororities and fraternities, have requested that the study space be reservable for events.
13. The [University student newspaper] conducted short interviews with professors about their thoughts on the new study space. Two-thirds of interviewed professors indicated that they would prefer for the study space to be mixed-use so that it could also function as a classroom.
14. [University] is concerned about recent reports of [Local] residents entering [University] buildings after-hours. The study space will be in a [University] building that requires swipe access between the hours of 10:00pm and 5:00am.
15. [State] Building Code requires that all rooms have a minimum of two safe egresses (such as doorways).
16. To address the issue of theft on campus, the President of [University] has made the decision to enhance security measures by installing security cameras in the study areas. This proactive step aims to deter theft incidents and provide a safer environment for students, faculty, and staff.

17. The donors who are sponsoring the study space have expressed their desire that acknowledgement of their sponsorship be prominently displayed somewhere in the study space. This acknowledgment should also highlight the donors’ commitment to fostering an exceptional learning environment for students.
18. Industry partners are eager to utilize the study space as a platform for promoting internships, job opportunities, and other initiatives.
19. [Local] high schools seek to collaborate with [University] and offer high school students the chance to immerse themselves in the university atmosphere and take advantage of the study spaces provided by [University]. This collaboration aims to cultivate a conducive learning environment, foster community engagement, and establish a smooth educational transition between high school and college.
20. To foster connections with undergraduate students and expand their professional networks, alumni want to organize weekly networking gatherings in the study space and hope this initiative provides a platform for alumni and undergraduate students to share insights, build relationships, and explore professional opportunities.
21. Government regulations are increasingly requiring the use of reusable and recyclable building materials to promote sustainability and reduce environmental impact.
22. [University] estimates they will go through a redesign process for this study space in 15 years.
23. Interior design reports from marketing experts consistently highlight the importance of creating study spaces that are easily accessible and easily navigable.
24. For the past five years a coalition of [Local] residents have been advocating for [University] to spend more money locally when purchasing materials and labor for campus projects.
25. Psychological research has highlighted the benefits of comfortable studying environments for students’ mental health. This research recommends that engineers and interior designers collaborate with psychologists when designing study spaces.