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Origins of Requirement Development Skills in Engineering Undergraduates: Students' Initial Thinking and Use in Engineering Decisions

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Abstract
A key challenge in engineering design problem framing is defining requirements and metrics. This is difficult, in part, because engineers must make decisions about how to treat qualitative and subjective issues, like stakeholder preferences, about how to prioritize different requirements, and about how to maintain tentativeness and ill-structuredness in the solution space. And this is made more challenging in light of the function of requirements in other types of engineering problems, like feasibility analysis, in which the requirements should converge on a decision. Given these challenges, it is unsurprising that there is limited research on how first-year students approach such work, how they make sense of requirements, and how their conceptualizations of requirements change with instruction. Our purpose in this study is to investigate students' initial understanding and use of engineering requirements in a specific problem solving context.

We developed a survey to measure students' perceptions related to engineering requirements based on constructs derived from the literature on engineering requirements. We implemented the survey in a first-year and in senior courses for the purpose of validating items using factor analysis. Following this, we conducted analysis of survey and interview data restricted to the first-year course, including epistemic beliefs and analysis of students' agency.

Through exploratory factor analysis, we found that factors did not converge around constructs as described in the literature. Rather, factors formed around the forms of information leveraged to develop requirements. Through qualitative analysis of students' responses on the survey and to interviews, we evaluated the extent to which students expressed agency over their use of requirements to make decisions within a course project. We describe implications of this exploratory study in terms of adapting research instruments to better understand this topic. Further, we consider pedagogical implications for first year programs and beyond in supporting students to develop ownership over decision making related to engineering requirements.

Introduction and research purpose
Our interest in this research work is tied to the idea that engineering practice is fundamentally about design [1], [2] of products, processes, systems, and services. Thus, in educating engineers, we must be attendant to developing skills that help students to traverse design problems. While some characterize design as a problem solving process [2], and disagreeing with this stance might seem surprising, we argue that problem solving is the best understood and least challenging aspect of design. In contrast, the effort to frame design problems stands out as one of the hardest topics to teach as well as to study. This is in part because framing and solving happen iteratively, as a co-evolutionary process [3]. In this study, we focus on the tipping point between framing and solving. Specifically, we view the development of requirements as the culmination of (re)framing and as the transition into solving the problem (Figure 1). However, a key challenge in this work is that we lack consistent terms, definitions, and practices related to engineering requirements. In our review of literature and curricula, we have found a host of related terms and tools, such as criteria, metrics, design requirements, engineering requirements, specifications, decision matrices, Pugh charts, House of Quality, and even pros and cons. To

address this lack of specificity, we conducted an exploratory study. We sought to answer the following research questions:

1. What latent factors does a new engineering requirements survey measure? What latent factors does an existing epistemic beliefs survey measure?
2. To what extent do first year students vary in their epistemic beliefs and perceptions of requirements, and is there a relationship between epistemic beliefs and perceptions of requirements?
3. How do first year students perceive and describe their approach to engineering requirements, and to what extent do they take agentive roles in this process?

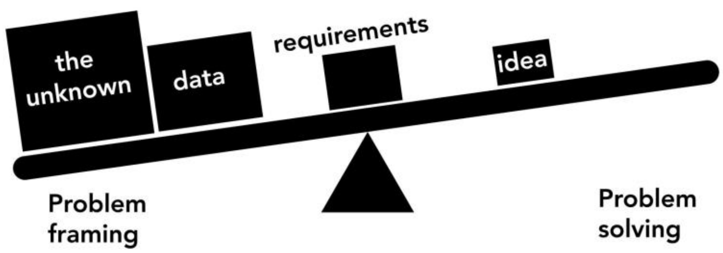

Figure 1. Requirements as the Pivot Point Between Problem Framing and Solving in Design

Framework

We agree with Dorst [4] that engineering design is a concurrent and iterative process of both framing and solving problems. Problem framing, especially early in design problems, often requires translating between qualitative and quantitative frames. This move from qualitative to quantitative representations is reflected in the descriptions of the design process found in numerous design texts [5]–[8] and in the research literature on designing [1], [9]–[11]. In translating from qualitative to quantitative representations, the ability to develop and set requirements is essential to the framing of problems.

Further, we contend that the technically-focused work of engineers – that which occurs in the latter stages of the design process – is largely dictated by a need to fulfill requirements set early in the process. This is reflected in the process of verification, an evaluation of whether or not a product, service, or system complies with set requirements (including regulations and standards) [12], [13]. Verification is part of the design process as described by standards set by organizations like the Project Management Institute, NASA, INCOSE, ISO, and the FDA [12]–[16]. During the course of design, engineers work with requirements in a variety of problem forms – e.g. case analysis, selection, troubleshooting [17], [18] – to ensure that the final design is capable of meeting those requirements. Therefore, as part of developing engineers who are prepared for the realities of engineering work as it occurs in practice, it is vital that engineering education attends to the development of problem framing and solving skills, inclusive of the formation of engineering requirements.

Engineering requirement skills of novices and experts

There is a significant body of research that characterizes differences between novice and expert designers [19]–[22] . However, there is limited evidence on differences between novice and experts in developing and working with engineering requirements, though there appears to be growing interest in this area. As Crismond and Adams [22] describe, beginning designers often skip over problem framing and go right to problem solving in the form of generating solution concepts, because they perceive design problems as more well-structured than they typically are. This includes a tendency to skip research – inclusive of researching standards and benchmarking of existing solutions – something that experts do throughout the design process. Even when novice designers carry out framing activities, like research, they still may have an underdeveloped understanding of the problem and a lack of justification for their framing. In analyzing the reports of capstone design teams to understand the development and justification of user requirements and engineering specifications, Loweth et al. [23] found that students' sources of information for user needs were often limited to interactions with sponsors and their own perceptions of user needs. Further, their engineering specifications were frequently derived from sponsor interaction, technical benchmarking, and prior work, and in some cases, specifications lacked a clear justification.

Mohedas et al. [24] investigated requirements development behaviors in seven novice designers, focusing on how they used available information sources across a six hour period to develop requirements for a given design scenario. They concluded that, in addition to time spent gathering information, strategies for gathering and synthesizing that information are critical factors in the formation of requirements. First, variance in the amount of time that two participants used in researching the available information sources versus synthesizing information to define requirements impacted the quality of requirements as assessed by stakeholders. This suggests that an important aspect of developing requirements is reliance on designers to analyze and interpret information; in other words, requirements are more than just objective facts that can be looked up. Second, they described "more advanced information gathering and use behavior" and "more advanced design process knowledge" in one participant, which supported a greater focus on requirements in stakeholder interviews and narrowing of the design task through the requirement development process. This behavior reflects an important element of problem framing to restrict the design space in constructive ways. Third, they described a dichotomy in how two novice designers considered the validity of stakeholder interviews. For one designer, information from the internet was more valid than information obtained from actual stakeholders, which they deemed "too anecdotal." For the other designer, who had the best evaluation of requirements of any designer, stakeholder interviews were as valid as any other information source.

Exemplifying the concurrent nature of problem framing and solving in design, Deininger et al. considered the use of prototypes by novice designers [25]. They found novice designers generally did not make use of prototypes to inform requirements definition. They attribute this, in part, to a lack of intentionality in the use of prototypes by novices. We speculate that because the academic experiences of novice designers so infrequently engender iteration, they fail to recognize that downstream design activities, like prototyping, are part of knowledge building that can inform reframing of problems, including requirements. Instead, design activities may be engaged or perceived as largely linear input/output stages.

From these studies, we see a clear need to further our understanding of how students develop the skills necessary for deriving and working with engineering requirements. The development of that skill should extend beyond obvious opportunities, like cornerstone and capstone design courses. Thus, this research is motivated to identify other places in the curriculum where this skill might be foregrounded and practiced. Important to identifying these opportunities, we need to define the key features of engineering requirements, which we consider in the next section.

Defining and characterizing engineering requirements

Engineering requirements frame the problem in engineering language (i.e., quantitative representation). As such, they are reductive, reformulating the complexity of a problem as experienced by (often heterogeneous) stakeholders into a concise set of measures, functions, and features. Thus, they reflect and mediate a shift from the often-qualitative expressions from stakeholders to quantitative expressions. Numerous texts and governing bodies describe features, processes, and language for the development of engineering requirements, yet as noted in the introduction, the term engineering requirements has many synonyms, and there is not a singular definition. To guide our research, we sought to develop a standard definition based on review of relevant sources.

Pahl and Beitz [5] describe a process for deriving specifications based on customer feedback that inform the embodiment and capability of the solution. They note that requirements should be quantitative whenever possible. Further, well written requirements allow for evaluation of a wide range of solution principles but levels of abstraction in the problem formulation are important to supporting this. If designers are trying to leave the design space as open as possible to encourage more innovative ideas, the problem framing (and thus, requirements) should be written in the most abstract terms possible and strive for solution independence [5]. As the solution principle takes more specific form, requirements become more specific, reflecting a convergence of problem frame and solution.

As part of Technical Processes (Chapter 4) INCOSE considers "Stakeholder Needs and Requirements Definition Process" and "System Requirements Definition Process" [14]. Through an input/output process series, stakeholder needs are transformed into stakeholder requirements, which are "transformed into system requirements," a process that is intended "to transform the stakeholder, user-oriented view of desired capabilities into a technical view of a solution." Through these processes, designers are instructed to identify solution constraints, and consider "critical qualities" in various categories like health, safety, security, and environment. The process descriptions focus on what activities to conduct but not how to conduct them. INCOSE describes 29 "characteristics and attributes of good requirements" including that the requirement is: "necessary," "implementation independent," "complete and measurable," "verifiable by inspection, analysis, demonstration, or test," and "conforming with existing regulations and standards" [14].

Various texts focused on mechanical product design present a similar definition for engineering requirements. Urban and Hauser [26] define engineering characteristics as "descriptions of the (eventual) design solution derived from the customer needs that are measurable and quantifiable." They describe the development of these characteristics as necessary to "describe the customer needs in the language of the engineer." Ullman [27] describes engineering specifications as a "restatement of the design problem (derived from customer requirements) in terms of parameters that can be measured and have target values." Similarly, Ulrich and

Eppinger [8] describe a need to translate customer needs to engineering specifications, which they define as “a precise description of what the product has to do; consists of a metric and a value.” They describe a four step process for translation: “1) prepare the list of metrics, 2) competitive benchmarking, 3) set ideal and marginally acceptable target values, and 4) reflect on results and process.” All three texts indicate that engineering requirements should be written in solution independent terms.

Based on the sources cited above, we use the following definition for engineering requirements (ERs): a set of parameters that describe the capabilities and behaviors of a system necessary to meet user needs and expectations; represented by a metric and a target value (e.g. “the weight of the system shall not exceed 2500 lbs”). Further, engineering requirements are often associated with the following characteristics, which form the basis for survey constructs and research interview questions described in the next section; ERs should:

- describe what the solution should embody, not how to do it (solution independence)
- be traceable to stakeholder needs (support validation)
- be quantitative and testable (support verification)
- be used as part of evaluating solution principles (support concept selection)

Epistemological beliefs and framing agency

Prior research has found that undergraduates may hold a range of epistemological beliefs on factors related to certainty and sources of knowledge [28]. Such research suggests some students may hold beliefs that engineering problems are well-structured and can be solved using certain knowledge that is shared via transmission, rather than constructed [28], [29]. Such beliefs may be fluid and contextualized by tasks [30]. Considering these prior findings, we sought to measure the epistemological stances of students in our study using items from the previously developed survey [28]. We conjectured that epistemological beliefs could explain variance in students’ perceptions about the development and use of engineering requirements. The development of engineering requirements reflects a specific and important form of knowledge construction in engineering, thus epistemological beliefs about the source and certainty of engineering knowledge may affect student perceptions about engineering requirements.

The work to define and use requirements is agentive, reflecting many consequential decisions, such as about what information to seek and when to seek it, what these indicate about stakeholder needs and how to prioritize them, etc. Due to their consequentiality to the problem frame, such decisions differ from other choices humans make. Recent research characterizes such decisions as *framing agency*, and details how such agency is detectable in how designers talk, highlighting that students’ prior educational experiences can constrain their expectations about their roles in framing problems [31]. We likewise conjectured that students’ perceptions of requirements and their role in defining them could be visible as framing agency.

Methodology

Survey development and exploratory factor analysis

To answer the first research question, we developed a survey and conducted exploratory factor analysis. We followed best practices in survey design [32], [33]. Specifically, we first reviewed literature to identify salient constructs and developed questions for those constructs (Table 1).

Table 1. Initial Constructs and Likert Questions

Construct & definition	*Questions*
Solution independence: Engineering requirements describe what the solution should embody, not how to do it in a design problem	How important or unimportant is it that engineering requirements describe what the solution should do, but not how to do it: ● when working on a feasibility problem? ● when working on a design problem?
Validity: Engineering requirements should be traceable to stakeholder needs	Crista collected customer data from interviews and surveys. Compared to other sources of data, how reputable or unreputable are data on customer needs? Eric collected data from an experiment; he tested materials properties over time. Compared to other sources of data, how reputable or unreputable are data from his experiment? Sam collected data from an internet search of existing solutions. Compared to other sources of data, how reputable or unreputable are data from this search? How important or unimportant is it that engineering requirements are based on stakeholder needs when working on: ● a feasibility problem? ● a design problem?
Subjectivity: Engineering requirements may be difficult to define for some stakeholder needs (e.g. “easy to use”)	If the team discovered that (1) there was a lot of uncertainty about whether mobile water purification would be acceptable to customers and (2) none of the vendors can feasibly produce a mobile solutions. How important is it to further investigate and resolve the uncertainty about customer acceptance in this case? How likely or unlikely are the engineering requirements to be subjective in: ● a design problem? ● a feasibility problem?
Comprehensiveness: Engineering requirements should include a comprehensive and multidimensional set of parameters	Crista collected customer data from interviews and surveys. Compared to other sources of data, how important or unimportant are data on customer needs? Eric collected data from an experiment; he tested materials properties over time. Compared to other sources of data, how important or unimportant are data from his experiment? Sam collected data from an internet search of existing solutions. Compared to other sources of data, how important or unimportant are data from this search? How difficult or simple would it be to develop a comprehensive set of engineering requirements for: ● a feasibility problem? ● a design problem?
Constrainedness: Engineering requirements impose endemic constraints, but leave problem open	The client provided customer data only from wheelchair users who have full use of their upper bodies. How appropriate or inappropriate would it be for them to include the ability to use upper body in their engineering requirements? If the team discovered that none of the vendors can feasibly produce a mobile solution, how appropriate or inappropriate would it be for them to change their scope of work by investigating the problem and changing the requirements? How likely or unlikely are the engineering requirements to highly constrain: ● a feasibility problem? ● a design problem?

We also developed constructed response items, in part because of the exploratory nature of this work, and in part to validate Likert scale items. The Likert items use a bipolar, 7-point scale with a midpoint, name the ends of the scale in the stem, and use construct-specific choices. We pilot tested the survey and sought expert review of the questions, revising items to enhance clarity.

In addition to measuring students' perceptions of requirements, we also selected items from a previously developed survey of engineering epistemic beliefs [28]. We focused on three subconstructs related to engineering knowledge: sources, simplicity, and certainty. Prior analysis of the full survey in the same context supported our selection of items.

We conducted exploratory factor analysis (EFA) to recover factor structure. We implemented the survey in a first-year (n=438) and in senior capstone design courses (n=186), a sample size more than adequate [34], [35]. We deployed the survey in multiple design contexts in order to capture greater variance present in the population, than might be represented at one educational level. We used the Kaiser-Meyer-Olkin (KMO) to measure the suitability of our sample for conducting factor analysis, using 0.5 as a cutoff [36]. We used Bartlett's test of sphericity to check the relationship between items, using $p < .05$ as a cutoff. We found that KMO was .57 and Bartlett's test of sphericity was < .001. We used principal axis factoring as our estimation method due both to its popularity and noted capacity for recovering factors with few items [37]. We used a promax rotation, which is oblique, meaning this approach allows items to be correlated with one another, as is typically assumed in social science research [38], [39]. We retained items provided they had loadings of at least .32 [38], and internal consistency of at least .50 using Cronbach's alpha, which lacks an agreed-upon cutoff [40]; we set a low cutoff given the exploratory nature of our work, but note limitations—namely, we have likely retained questions that in future studies may be removed. We removed any items that cross-loaded on multiple factors. We re-ran the factor analysis with the retained items, creating a parsimonious model.

Mixed methods research design

To answer the second and third research questions, we used a mixed-methods approach, considering survey responses and interviews. These data are limited to first-year engineering undergraduates in a 3-credit hour engineering seminar. The seminar comprises lecture and laboratory components in which students work through a range of engineering problem scenarios intended to get them to "think like an engineer," as described to us by the instructor. Students engage different types of problems, like selection of an alternative fuel policy based on qualitative assessment and quantitative modeling, and configuration design of a small scale wind turbine kit. They also learn about specific engineering disciplines and problems through guest speakers from industry and academia, and through career exploration activities. Students are supported in these activities by multiple faculty and student mentors who range from sophomore through senior year.

We conducted statistical analysis of the survey data, inclusive of descriptive statistics, correlation, and comparative analysis of factors. We analyzed constructed response items on the survey (Table 2). Specifically, we examined items for students' conceptualization of requirements, informed by the constructs we sought to measure in the survey, but grounded in the data. In particular, we coded students' responses to "How would you explain the concept of engineering requirements to a high school student?" This question was preceded by the definition below, yet we noted variability on how students answered the question.

- ENGINEERING REQUIREMENTS are a set of parameters that describe the capabilities and behaviors of a system necessary to meet user needs and expectations. Engineering requirements are criteria typically represented by a metric and a target value (example: system weight (lbs.) shall not exceed 25 lbs.).

Table 2. Coding Scheme for Constructed Response Items

Construct	***Markers***
Solution independence	Does not characterize requirements as dictating what designers do. Attributes requirements to system or solution.
Validity	Mentions customer, consumer, user, stakeholder, etc. as source of need
Subjectivity	Mentions subjective options, such as wishes, desires, preferences, or wants
Comprehensiveness	Characterizes that there is a set or details multidimensional examples
Constrainedness	Mentions constraints or ways the problem is limited, bound, restricted, or restrained

We interviewed 16 students after they completed their first mini-project. The problem scenario is a policy problem [41] in which students are asked to provide a recommendation to the U.S. Energy Department regarding a strategy for investment in energy sources. Students are asked to consider eight different energy sources, through qualitative and quantitative frames. Their qualitative consideration is facilitated through a decision matrix, inclusive of six criteria (technical feasibility, economic viability, capacity/sustainability, vulnerability/stability, environmental impact, and geo-sociopolitical impact). Their quantitative consideration is facilitated through modeling for four of the fuel alternatives (ethanol, biodiesel from soy, biodiesel from algae, and synfuel from coal) in which they are asked to estimate the resource capacity limitations. For example, there is a limited amount of land that can be used to grow soy, which impacts the viability of biodiesel from soy. The decision matrix and quantitative modeling work is carried out as a group activity, in a lab setting. Each student submits an individual written recommendation.

We followed a semi-structured interview protocol based on questions derived and aligned to the constructs described in Table 1. There were a total of 16 interview questions but only those reported on in this study are shown in Table 3. At the start of each interview, we told the student that we would use the term “metric” throughout the interview, and asked: How have you seen the word metric used in your course? The decision to use metric instead of engineering requirement was made in consultation with the course instructor. He indicated that “metric” is used throughout the course and that its meaning is aligned with the definition of engineering requirement that we have derived and used in the survey.

We transcribed the interviews and analyzed them with attention to how students conceptualized requirements and metrics in the context of a course assignment (Table 4), with attention to how students justified their prioritization of metrics as part of the alternative fuels project. We followed this with a discourse analytic approach that brings attention to levels of agency as expressed in verbal clauses, relying on sentence subjects (e.g., I, we, it, etc.) and verbs that show potential (e.g., could, can), no control (have to, required to), versus full control.

Table 3. Focal Interview Questions, Linked to Construct

Construct	*Interview question*
Alignment with course	We will use the term "metric" in our conversation today. How have you seen the work metric used in your course?
Multiple	Can you tell us a little about the project you are working on now in your course, or, if you just completed a project, tell us about that?
Validity	Did you prioritize some metrics? Did you use all the [requirements] metrics you came up with, or find some to be less important?
Validity	What did you rule out? How and why?
Validity	How did you prioritize? How and why?

Table 4. Coding Scheme for Interviews, Focused on How Students Prioritized Metrics

Code	*Description*
Problem endemic	Justification rooted in their beliefs or approach in the context of the problem
Class-constrained	Justification based on beliefs about what they were supposed to do for the class but may not authentically reflect engineering practice
Data availability	Justification based on availability of data or information, which is limited to research or provided data

Results and discussion

We organize our results by research question, first presenting the results of factor analysis, then investigating various sources to better understand students' initial approaches to requirements.

Factor analysis results

We anticipated a five-factor solution aligned to requirements subconstructs— solution independence, validity, subjectivity, comprehensiveness, and constrainedness. However, we recovered only two factors, and these were aligned to different data types students encounter in defining requirements (Table 5).

Table 5. EFA Results for Engineering Requirements Items, Parsimonious Model (Bipolar, 7-point Likert scale, e.g., Very unimportant to Very important)

Item prompt	*Factor loading*		*Mean (SD)*
Factor: Role of Customer Data in Determining ERs (α = 0.52)			
Crista collected customer data from interviews and surveys. Compared to other sources of data, how important or unimportant are data on customer needs?	**0.79**	0.01	6.16 (1.25)
Crista collected customer data from interviews and surveys. Compared to other sources of data, how reputable or unreputable are data on customer needs?	**0.46**	-0.06	5.51 (1.22)
Factor: Role of Internet Searches of Solutions in Determining ERs (α = 0.55)			
Sam collected data from an internet search of existing solutions. Compared to other sources of data, how important or unimportant are data from this search?	0.03	**0.76**	5.52 (1.19)
Sam collected data from an internet search of existing solutions. Compared to other sources of data, how reputable or unreputable are data from this search?	-0.08	**0.49**	5.99 (1.08)

Table 6. EFA Results for Epistemological Beliefs for All Data (Bipolar, 7-point Likert scale, Strongly disagree to Strongly agree)

Item prompt	*Factor loading*		*Mean (SD)*	*α if deleted*
Factor: Certainty of Engineering Knowledge (α = 0.627)				
Engineering problems have only one right answer.	-0.05	**0.66**	1.47 (0.77)	0.53
There is one universal engineering method.	0.03	**0.49**	2.11 (1.34)	0.69
All engineering experts understand engineering problems in the same way.	-0.02	**0.79**	1.69 (0.93)	0.41
Factor: Source of Engineering Knowledge Understanding (α = 0.680)				
The best way to develop engineering knowledge is by an engineering expert transmitting his or her knowledge to us.	**0.44**	0.24	3.86 (1.50)	0.65
A theory in engineering should be accepted as correct if engineering experts reach consensus.	**0.50**	0.12	4.12 (1.40)	0.63
Engineering students learn when a teacher or expert transmits his or her knowledge to them.	**0.58**	0.05	4.93 (1.32)	0.62
Engineering knowledge should rely on a combination of experts' observation, experimental evidence and rational arguments.	**0.57**	-0.19	6.02 (1.06)	0.65
New engineering knowledge is produced as a result of controlled experimentation.	**0.52**	-0.10	5.07 (1.24)	0.65
Engineering knowledge is an accumulation of facts.	**0.48**	-0.01	4.96 (1.37)	0.65

We anticipated a three-factor solution for the epistemological beliefs survey, given past research on this survey [28]. Instead, we recovered two factors (Table 6). Certainty of engineering knowledge aligned to prior studies. Students who agree with these items hold beliefs that engineering problems are well-structured. The second factor combined items about the source of engineering knowledge and its simplicity; this aligns to recent research suggesting simplicity of knowledge, as measured by the existing items, is not conceptually clear enough [42].

Characterizing students' epistemic beliefs and perceptions of engineering requirements
Based on the results of factor analyses, we focused analysis of first-year students' responses primarily on the recovered factors. First, we found that overall, students reported disagreement that engineering knowledge is certain (Figure 2, n = 435; M = 1.75; SD = 0.77). Second, we found that overall, students somewhat agreed that engineering knowledge is sourced from experts (n = 431; M = 4.81; SD = 0.81). This stance would suggest that, when faced with the task of defining engineering requirements, students would tend to view extant information, including existing sources and solutions, as more valid than information gained via their own efforts—specifically, via their own experimentation and interviews with customers.

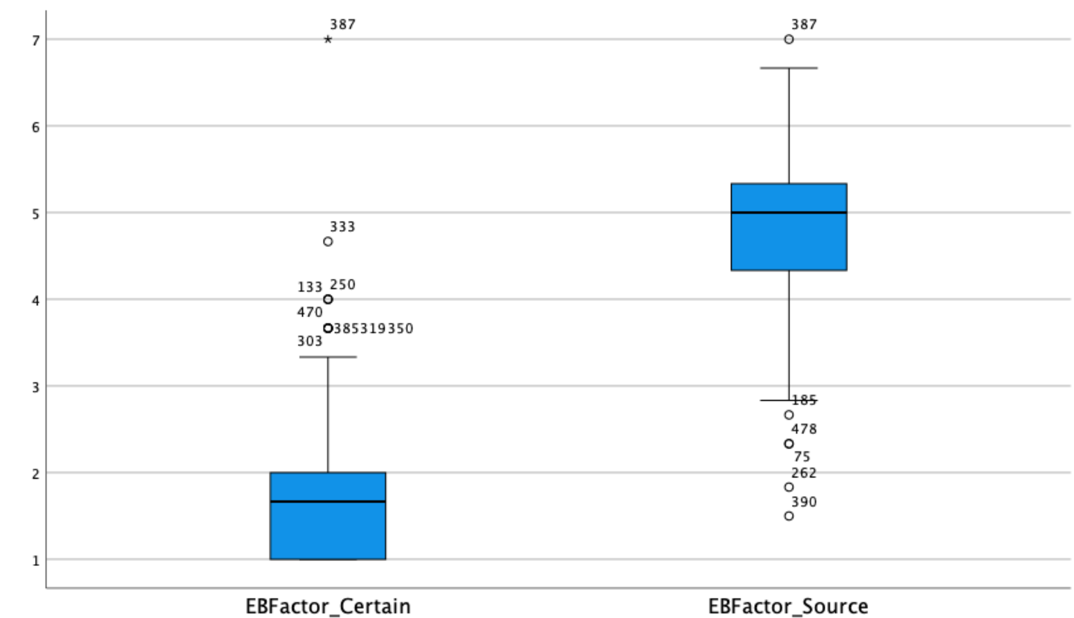

Figure 2. Boxplot of Epistemological Belief Factors for First-Year Students

In terms of students' perceptions of engineering requirements, we first focus on the recovered factors. Students rated information from customers significantly more highly (Figure 3, M = 5.82; SD = 1.02) than information about solutions gained from internet searches (M = 5.02; SD = 1.02), $t(435) = 13.05$, $p < .001$. This result seems to counter our findings for epistemological beliefs, however. We therefore conducted bivariate correlation analysis, conjecturing a relationship between epistemological beliefs and perceptions of requirements. Knowledge certainty and sources were significantly and positively correlated $r(431) = .18$, $p < .001$, as were perceptions about requirements $r(436) = .23$, $p < .001$, but we found no significant correlations between epistemic beliefs and perceptions of requirements.

Collectively, the survey results suggest the first year students generally held desirable epistemological beliefs, leaving them open to problem framing, but perhaps somewhat uncertain about their roles in knowledge generation. Yet they reported valuing information that is more subjective. To better understand these trends, we consider insights gained from the interviews and constructed response items on the survey.

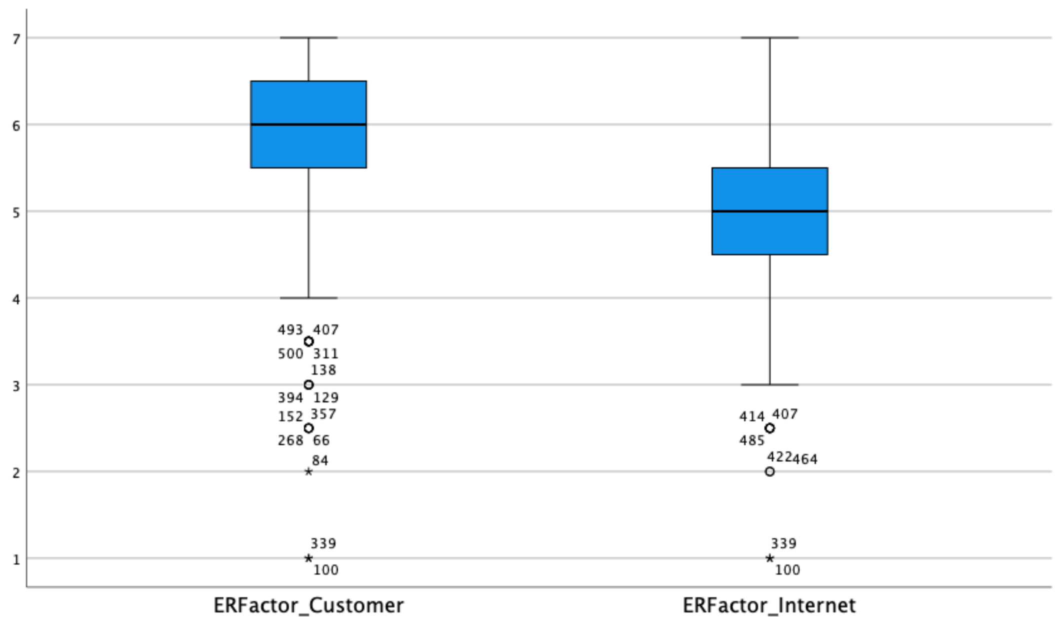

Figure 3. Boxplot Engineering Requirements Factors for First-Year Students

Exploring students' early understandings of engineering requirements

In the constructed-response items, we found many students took up elements of the definition provided, such as attributing requirements to the system/solution, rather than proscribing actions or behaviors of the designer (Figure 4). One third mentioned stakeholder needs (validity), and one quarter referenced comprehensiveness via a set or framework. A few students introduced accurate ideas that were not present in the provided definition, including that needs may be subjective and that some requirements can be considered as constraints. Additionally, a few students equated requirements only to constraints, and approximately one fifth of students offered unelaborated explanations of requirements as criteria.

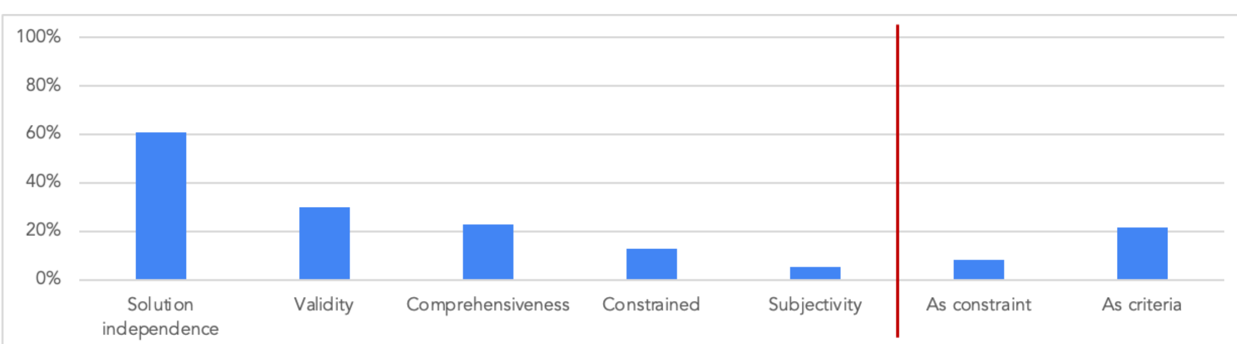

Figure 4. Qualitative Analysis of First-Year Students' Explanations of Engineering Requirements

With respect to interview questions about the prioritization of metrics, 12 students indicated that they did prioritize some metrics over others (Table 7). We found that the justifications tended to fit three categories as described in Table 4.

Table 7. Qualitative Analysis of Student Interviews

Code (students)*	*Example*
Problem endemic (Evan, Heather, Kurt, Val, Usef, Nick)	"I took the current circumstances of what's necessary into consideration. Like, right now, in, in America, worldwide, something that's very important is the environmental impact of this alternative fuels, because that's why we're finding alternative fuels, because of the negative impacts that crude oil and petroleum have created."
Class-constrained (Carrie, Ian, Jessie)	"Um definitely we prioritized capacity, just because our equations, because pretty much the the equations they gave us, well I guess that we worked on in lab, but that was their main focus."
Data availability (Adam, Ian, Janelle, Tina)	"Mostly, I would look for something that had concrete evidence and research. So, mostly like, academic, academic papers on what the yields were for certain fuels and how much of that we have and how easily we can obtain that."

*Names are pseudonyms

In discussing metrics and prioritization, students varied in how they used their agency, and we consider how their talk varied given how they explained their prioritization. Those who described metrics as endemic to the problem tended to use more middle-ground agency (an average of 38% of their talk, compared to 24% in the class-constrained and 20% in the data-availability groups). Specifically, they attributed agency in tentative ways, such as when Val considered "will this contribute to climate change at all or to the greenhouse gasses?" or when Usef explained his reasoning about why environmental concerns mattered more, "the least beneficial would be, like geo, social, political." They shared their agency with teammates (Val: "we're trying to find a fuel"), sometimes also showing tentativeness characteristic of framing agency (Kurt: "we would also want one that's cheap enough for people to be using it and prioritizing it over regular gasoline."). In contrast, shared tentative talk by Adam seemed to distribute the consequences for not finding information ("we're going to evaluate a little bit less, talk about it a little bit less, still address it, but not as much as the others"). Carrie tentatively attributed her agency to the instructors, ("Maybe if they gave a little bit of more information, like if they gave us a packet saying these are your assumptions")

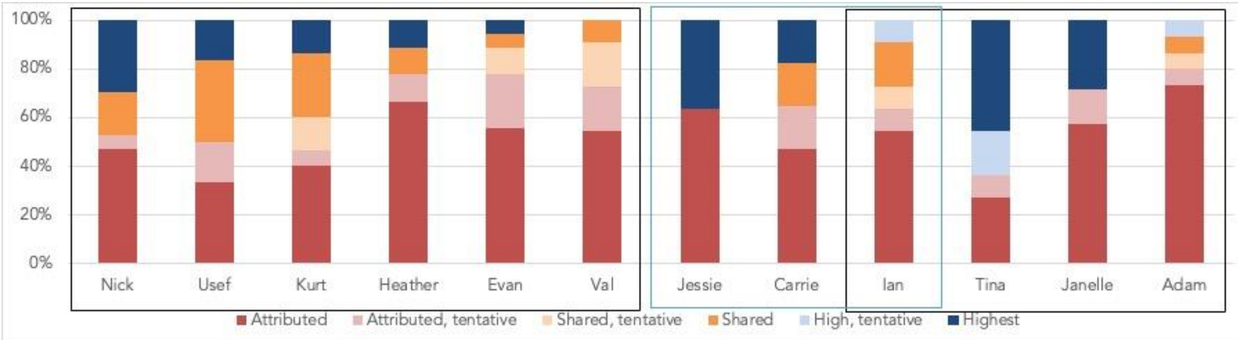

Figure 5. Students' Agency in Discussing Prioritization

Conclusions, limitations, and implications

In this study, we sought to develop tools and understandings of students' early perceptions of engineering requirements. We conjectured that their epistemological beliefs, especially related to the source and certainty of knowledge, should be related to their perceptions of engineering requirements, but we did not find support for this conjecture. This is perhaps because of somewhat limited variability in students' epistemologies. We found that most students held stances that engineering knowledge is not certain and showed openness to the sources of engineering knowledge.

We sought to develop a survey to measure students' perceptions of engineering requirement subconstructs (validity, constrainedness, solution independence, subjectivity, and comprehensiveness). Instead, recovered factors focused on different sources of information. Students reported that data from customer interviews is more important than data on solutions gained from internet searches. Qualitative analysis of students constructed responses showed that students particularly attended to the notion that requirements describe the function of a system or solution, are sourced from stakeholders, and are a multidimensional set of parameters. In analysis of interviews, we found that students tended to view requirements in one of three ways: as endemic to the problem, as an artifact of the difficulty of simply finding information, or as tied to the inauthenticity of classroom activities.

Our results suggest that further work is needed to develop items capable of measuring engineering requirements subconstructs. In our ongoing work with interview data, we plan to develop new questions that are more grounded in the terms students use and that capture the variability present in their accounts. We likewise see potential in situating the epistemological beliefs items in the requirements context to prompt linkages. A context dependent epistemological perspective aligns with findings of Gainsburg in studying the epistemological stances of engineering students with respect to mathematical methods [43].

Collectively, our results suggest students may be more open to learning about requirements and using them, yet we know that instruction does not always capitalize on this potential, in some cases because of the scale of first-year class size or because of a need to accommodate specific ABET criteria. For example, going beyond internet- and paper-based research to incorporate talking with stakeholders or conducting an experiment to inform requirements could make for a richer learning experience more analogous to engineering practice. However, the infrastructure and teaching resources necessary to scaffold such experiences for 400 students may not be feasible in cost or time. Similarly, a change to the problem scenario could make the addition of these other knowledge building experiences more feasible. However, such changes may take away from the course's ability to address ABET criteria related to developing students' recognition of global, cultural, social, and environmental factors in engineering solutions. Finally, some institutions use first year experiences as exploratory mechanisms and may include students who are interested in engineering and others who are not sure of their interest. Activities built around problem framing, like developing engineering requirements, can allow students to work between qualitative and quantitative representations of problems. This may prove to attract more students to engineering because it shows that engineering is more than just rational application of math and science. However, students may feel deceived once they get further into the engineering curriculum when coursework becomes math and science focused. These challenges speak to the heavy-lifting expected of first-year courses to give students insight into the profession, while potential to incorporate these important forms of learning related to design in the middle years has largely been ignored [44]. Likewise, we note that students' prior educational experiences can constrain their expectations, leading them to assume that course-based activities are inauthentic, making the work of offering a lens into professional practice all the more difficult.

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