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Engineering requirements and their role in engineering undergraduates' design decision making

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Abstract

Undergraduate engineering students are commonly introduced to design in their first year and tackle a more authentic design challenge during senior year, with intervening courses focused on technical problem solving. Along this trajectory, students should acquire skills related to the development of engineering requirements, which are important to the technical framing of design problems. Through the lens of framing agency, this mixed-methods study explores first-year and senior students' knowledge of engineering requirements as they engaged problems within their respective courses. Findings suggest that learning about requirements as a framing mechanism was not well-supported across the curriculum. Implications include a need to engage students in requirements development during the middle years and improve support for iterative framing and solving activities.

Keywords Framing · Decision making · Design education · Engineering design · Design discourse

Introduction

Engineering requirements play an important role in the development of products and systems. Derived from stakeholder needs, regulatory standards, and engineering codes, setting requirements is critical to establishing and constraining the design space in which engineers make decisions. Design texts, from fields like engineering, human factors/ergonomics and human centered design (Marek et al., 2010; Pahl & Beitz, 2007; Spirochkin, 2023; Steinfeld, 2012; Wilson & Sharples, 2015; Zenios et al., 2009) referenced in courses across engineering disciplines foreground engineering requirements (which are also known as design specifications, design requirements, product specifications) as a critical early stage of design (Ogrodnik, 2019; Pahl & Beitz, 2007; Towler, 2022; Ullman, 2010; Ulrich & Eppinger, 2011). As the design process progresses, requirements govern development decisions and must ultimately be verified

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and validated as described by standards of practice set forth by organizations like the International Council on Systems Engineering, the U.S. Food and Drug Administration, and NASA (Health, 1997; International Organization for Standardization (ISO), 2015; NASA, 2007; Project Management Institute, 2017; Walden et al., 2015).

Design is central to engineering, (Dym et al., 2005) and the specification of engineering requirements is essential to informing a range of activities – analyzing, prototyping, experimenting, etc. – at the heart of engineering practice. The specification of engineering requirements represents a critical phase in design by which the problem representation transitions from a qualitative to a quantitative one. That transition is fundamental to the framing of a problem and scoping of subsequent problem solving activities. Considering the important and complex role of requirements in engineering problems, deriving and working with requirements is an important skill for engineers to develop as part of their education. Arguably, ABET criteria engender this capability in the expectation that graduates of accredited programs demonstrate "an ability to identify, *formulate,* and solve complex engineering problems by applying principles of engineering, science, and mathematics" (emphasis added) (ABET, 2022). The specification of engineering requirements is fundamental to formulating problems.

In this study, we sought to explore students' perceptions and experiences with engineering requirements and how their thinking might evolve across their undergraduate careers. We considered the experiences of first-year and senior students as it relates to the framing of problems through engineering requirements in different problem contexts. We explore two research questions in this work:

RQ1: To what extent do student perceptions about engineering requirements change with design education?
RQ2: What agentive roles do students take in developing and using engineering requirements to frame problems?

In exploring the first question, we analyzed the pre/post responses of a survey issued in a first-year engineering course sequence and the senior capstone design courses in mechanical and biomedical engineering programs. To answer the second question, we considered a series of interviews conducted with students from both the first-year and capstone course settings.

Background

This study explores the perceptions of engineering undergraduates as they engaged in projects and assignments intended to provide authentic, design learning experiences. Endemic to authentic experiences is the presence of engineering requirements, over which students had varying degrees of agency. As noted previously, establishing engineering requirements (ERs) is fundamental to formulating problems – i.e., ERs inform both the framing of the problem and scope of activities necessary to design a solution. We review literature on ERs and their role in framing and solving, what is known about and approaches to supporting students to learn how to set and use ERs, and the importance of agency in both setting ERs and learning to do so.

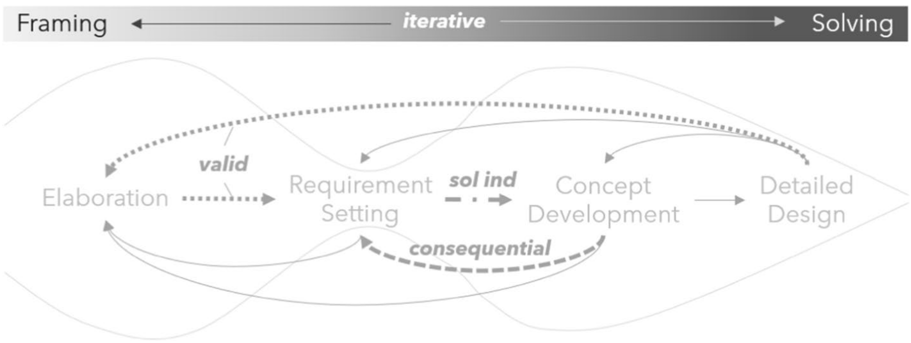

Fig. 1 Representation of design process (as framing and solving) as a process of elaboration, requirement setting, concept development and detailed design. Three engineering requirements parameters—solution independence, validity, and consequentiality—are placed as pathways across these processes

Setting requirements mediates the two worlds of framing and solving

Across design research and practice, there is evidence that requirements play a mediating role between problem framing[1] and problem solving, functioning to establish both performance parameters and constraints that bound the solution space. Across design fields, the particular framing practices vary, but commonly aim to gather information about the problem, identify needs, and set bounds or structure the problem space (Atman et al., 1999; Schön, 1984). For instance, a multiple case study of framing in social innovation design projects highlighted that such projects depend on divergence from an initial problem brief, driven by research and engagement with stakeholders (Bijl-Brouwer, 2019). We consider this to be a process of elaboration to understand the problem from various perspectives (e.g., stakeholder needs assessment, contexts of use, environmental conditions). In disciplines like engineering, designers often contend with sociotechnical problems in which the information they gather includes both qualitative and quantitative data; (Law, 1987; Trevelyan, 2010) in turn, they make decisions to frame the problem using these different forms of data.

Requirement setting is among the “structuring actions” that allow designers to navigate the underdetermined nature of design problems (Dorst, 2004). In practice, this inflection point is often situated within an overarching process of design that, while messy, can be (and frequently is) presented as a series of stages – e.g., (NASA, 2007; Pahl & Beitz, 2007; Ulrich & Eppinger, 2011) – that can be further abstracted as a co-evolutionary process of framing and solving (Dorst, 2019). Such a process abstraction is shown in Fig. 1, wherein requirement setting mediates early design activities focused on problem elaboration and downstream activities focused on concept development and detailed design. The action of

[1] Terms such as problem scoping, problem framing, problem formulation, problem representation, and problem definition are not used consistently across scholars and are sometimes interchangeable; for instance, some scholars reference the findings of Atman and colleagues (who prominently refer to scoping) using the terms framing and scoping interchangeably e.g., (Williams et al., 2012). Likewise, Atman and colleagues (and others) reference work by those who exclusively discuss framing: (Cross, 2001; Cross & Cross, 1998; Schön, 1988), yet refer to that work as scoping. We prefer the term framing.

requirement setting is a critical pivot point at which designers transition from one world (framing the problem) to another (solving the problem).

With reference to design texts and sources, we define engineering requirements (ERs) as: *a set of solution independent, valid, and consequential 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").* These parameters, investigated in this research, are defined below:

- Solution independent: ERs should provide solution agnostic framing; they specify what a solution should provide, but not how to provide it. Ideally, ERs are developed prior to concept development to avoid bias and/or artificially constraining the solution space (Pahl & Beitz, 2007; Ulrich & Eppinger, 2011).
- Valid: Designers ensure that outcomes of a solution meet stakeholder needs (NASA, 2007; Walden et al., 2015); it is important that stakeholder needs articulated during elaboration inform the development of ERs and are ultimately traceable in the qualitative to quantitative transformation of problem framing. Increasingly, design practice in multiple domains centers on understanding and developing requirements based on individuals, as in human factors/ergonomics (Marek et al., 2010; D. A. Norman, 2013; Spirochkin, 2023), universal design (Steinfeld, 2012), and user experience (UX) design (Canziba, 2018).
- Consequential: The ERs fully represent the problem and support evaluation of solution concepts; ERs provide a quantitative framing mechanism by which designers can make decisions and tradeoffs among various stakeholders and accommodate (hard and soft) constraints.

These parameters, as reflected in Fig. 1, demonstrate the critical role that ERs play as a framing mechanism that mediates forward and backward movement, along specific pathways, through the design process.

Undergraduate experience with problem framing and engineering requirements

Given their import, design education should facilitate engagement with requirements as an important aspect of learning to frame and solve problems, with students playing a role in both defining requirements and specifying their target values as a way of framing the problem and as a precursor to developing solutions that address the underlying problem.

Prior research on student design capabilities found that achieving better solutions coincided with seniors' superior ability to gather adequate information, setting up the problem, and making more transitions between steps than first-year students (Atman et al., 1999). This echoes findings on similar activities studied as problem framing (Ahmed et al., 2003; Mehalik & Schunn, 2006; Schön, 1988; Valkenburg & Dorst, 1998; Zahedi, 2016) showing experienced, skillful designers engage in framing and reframing deliberately and repeatedly, throughout the design process. Likewise, experienced designers pay better attention to customer needs, logistics, and constraints in the design task (Bogusch et al., 2000).

However, research specific to students' ability to develop and use requirements as a framing mechanism suggests that fostering this particular design skill requires additional support. In analyzing capstone design teams, (Loweth et al., 2020) found that requirements were frequently derived second hand and sometimes lacked a clear justification.

Requirement development might also be informed by activities like reverse engineering and prototyping. However, there is evidence that novice designers' use of prototypes lacks this type of intentionality (Deininger et al., 2017). Mohedas and colleagues (2015) investigated requirements development behaviors among senior biomedical and mechanical engineering students on an 8-h toy design task, finding that few students produced valid requirements that were tied to the specific context. Further analysis showed that those who developed more valid and contextual requirements relied on diverse sources of information, and especially used sources beyond the internet. They concluded that students benefit from support in gathering and synthesizing information in the formation of requirements.

Requirements from stakeholder needs can be derived from evolving methods rooted in user experience (Canziba, 2018; Silva da Silva et al., 2012), human factors/ergonomics (Spirochkin, 2023; Wilson & Sharples, 2015), and universal design (Steinfeld, 2012). However, while students report valuing stakeholder needs, they seldom gathered adequate data from stakeholders (Loweth et al., 2020). Adequate engagement with stakeholders by students can be influenced by varied issues, like ambiguity in the problem definition, beliefs about who constitutes a stakeholder, the relevance of stakeholder information, and a lack of quantitative information from stakeholders (Mohedas et al., 2023).

When a designer makes decisions about what information to gather, when adequate information has been gathered, and strategies for synthesizing that information they are exhibiting *framing agency*—the capacity to make consequential decisions about how a problem is framed. A practical outcome of that agency is a set of engineering requirements to be met by the solution. In supporting students' agency in design contexts, practice specific to the development of requirements is critical.

Forms of agency in design

Traditional descriptions of agency define it as a human act of making a decision but constrained by structures (Emirbayer & Mische, 1998; Giddens, 1984). Depending on the actor, agency over a problem may be constrained authentically (e.g., as a function of available resources) or inauthentically (e.g., as a function of long practiced social norms). Designers exercise agency over a variety of decisions throughout the design process, like concepts to consider, material choices, component suppliers, and manufacturing processes. These aspects of design are more obviously situated in the problem solving stage of design. However, agency over decisions is also important to initial framing and reframing of problems and may include identifying stakeholders, use contexts, benchmarking existing solutions, and setting requirements (Svihla et al., 2021). Designers must have agency to set requirements, but agency is not free will; agency is distributed as the client, stakeholders, and problems have agency too. For example, the design of a cell phone must consider battery life. Stakeholders will naturally want a long battery life but also a form factor that is suitable for carrying around. Designers must set relevant requirements (e.g., battery life, battery size) that trade off among conflicting stakeholder needs and thus share agency with those stakeholders and the material properties. This shared framing agency is problem-endemic and represents an important aspect of authentic practice.

Within engineering education environments, students' problem engagement often takes inauthentic forms owing to a focus on well-structured problems, focused on technical knowledge (Jonassen, 2014) and a perceived limitation of what actions are allowed or expected. Important forms of authentic practice – e.g., context and task authenticity (Strobel et al., 2013) – are often not present in design problem scenarios. Further, and perhaps owing to a lack of authenticity in educational settings, novice designers have been found to move ahead with design problem solving before the underlying problem is adequately framed (Crismond & Adams, 2012; Silk et al., 2021; Svihla et al., 2021).

The current study is motivated by our understanding of problem framing, student experiences with framing in general, and ER development specifically, and limited research on student experiences with ER development. Given the nascent state of this topic, this study took an exploratory approach, as described in the next section.

Methodology

This study used a mixed-methods approach, inclusive of a pre/post survey and a series of interviews with students from a first-year engineering seminar and senior capstone design courses in biomedical (BE) and mechanical engineering (ME). In this section, a brief overview of the participants and the courses from which they were recruited is provided. Additionally, the survey design, interview protocol, and analysis methods are described. The study was approved by the IRB (study #5766); we had a waiver of documentation of signed consent for survey data and collected signed consent for interviews. Interviewees were compensated $10 U.S. per interview. Since this study occurred in an academic context, to minimize both the influence of grades on study results and coercion, we took two steps. First, the survey was included by faculty as part of course assignments rather than extra credit, as this reduces coercion. Students who completed the survey were given a few points for completion, regardless of how they answered, and this was indicated in the survey instructions. Second, the interviews were completely voluntary and students were able to enroll in that portion of the study through a digital form that only researchers had access to. Faculty were not aware of which students participated.

Course overview and research participants

First-year seminar sequence

The first-year seminar comprises fall and spring courses. As described by the lead instructor, the goal of the seminar sequence is to get students to "think like an engineer." The fall course is 3-credit hours and includes lecture and laboratory components. The spring course is 1-credit hour. Across the sequence, students engage different types of problems, which include elements of design, analysis, and selection (decision-making). Students are supported in these activities by multiple faculty and undergraduate mentors. Problem engagement throughout the seminar sequence is scaffolded through a generalized engineering process model: 1) define the problem, 2) describe system operation, 3) generate alternatives, 4) compare alternatives, 5) model the performance, and 6) engineering recommendation. Stage 4 includes the development of requirements (metrics). Relevant to this study are three assignments students discussed in interviews.

- *Alternative fuels selection problem (fall):* The scenario is a policy problem (Jonassen, 2010) in which students provide a recommendation to the U.S. Energy Department regarding a strategy for investment in energy sources. Students consider eight different energy sources, through qualitative and quantitative analysis.

- *Wind turbine design problem (fall):* The scenario is a design configuration problem in which teams are provided a scaled wind turbine kit. Problem engagement is primarily focused on experimenting with combinations of design factors (e.g., turbine blade material, blade length, number of blades, gear ratio, generator type, stability) to find a configuration that maximizes power output.
- *Impact paper (spring):* Students work in pairs and identify an engineering problem that holds personal interest. Students develop an engineering project proposal or an engineering research analysis. The final report includes sections that closely mirror the engineering process model.

Subsequent to the first-year experience, students across disciplines engage the middle years curriculum. Like many degree programs, this part of the curriculum is focused on technical content and well-structured problem solving activities. (Lord & Chen, 2014) Engagement with design problems, particularly framing of those problems, is limited during these years. During senior year, many undergraduates engage in a year-long capstone design experience, like the mechanical (ME) and biomedical (BE) engineering participants in this study.

ME capstone design

The ME capstone experience is a two semester sequence. Students work on teams of 4–5 students to engage a design problem of their choosing. Problems are sourced from industry, faculty, or can be self-defined. During the fall semester, students learn design theory and methods as formally described in design texts and have assignments and exams related to these lessons. Design project work during this semester traces the design process as described by Dieter and Schmidt. (Dieter & Schmidt, 2009) This includes user needs assessment, benchmarking of existing solutions, development of product specifications, concept generation and selection, preliminary/detailed design in the form of an initial CAD model. The development of specifications (engineering requirements) is an explicit design task. During the spring semester, project work continues with further detailed design supported by analysis and prototype testing. This semester is intended to allow students time to iterate toward their final designs, thus there are few formal class meetings.

BE capstone design

The BE capstone experience is also a two semester sequence. Students work on teams of 4–5 students to engage a design problem. Problems are typically sourced from faculty in the BE department, the school of medicine, and clinical practitioners connected with the university. Similar to the ME sequence, the course follows a process of design for medical technologies as described by (Zenios et al., 2009). Students learn about design methods (e.g., stakeholder analysis, effective brainstorming) and considerations in medical contexts and have associated quizzes. Design project work in the fall semester includes identification of functional requirements, generation of solution principles, development of a working prototype, and a final design proposal. In the spring semester, project work continues with further design iteration and testing. There are no formal lectures.

Survey design and analysis

Survey design

Toward investigating student understanding about engineering requirements, we developed an exploratory survey (Table 1) following best practices in survey design (Dillman et al., 2014; McCoach et al., 2013). Through review of relevant literature, salient parameters—solution independence, validity, and consequentiality—related to engineering requirements were identified as previously described. The survey asked students to consider two engineering problem scenarios, a design problem and feasibility study, and more general questions. Items were mapped to a seven point Likert-scale, with 1 anchoring the low end of the scale (e.g., very unimportant) and 7 anchoring the high end (e.g., very important). In developing the survey items, questions were developed that might indirectly relate to the parameters.

The survey was conducted twice: at the start of the fall 2021 semester (pre) and at the conclusion of the spring 2022 semester (post). The pre survey was completed by 438 first-year and 194 senior students (130 ME, 64 BE). The post survey was completed by 262 first-year and 72 senior students (50 ME, 22 BE).

Survey analysis

We used a mixed ANOVA consisting of within-subject repeated measures (time: pre and post), as well as a between-group (first-year versus senior) analysis and interaction (group*time) analysis. Given the nature of survey data, we anticipated skewed data (Table 1). We checked assumptions related to normality and homogeneity of variance using the Shapiro–Wilk and Levene's tests, respectively (Field, 2013). Shapiro–Wilk tests for all three items for each group were significant ($p < 0.05$), indicating non-normal data. Similarly, Levene's test proved significant at two points indicating non-homogeneity of variance (Table 1). Despite these limitations, we report the results of our mixed repeated-measures ANOVA because failure to meet these assumptions should not necessarily invalidate the analysis (Field, 2013). Researchers have discussed the challenges of meeting these assumptions with survey data and have noted that the robustness of parametric methods, like ANOVA, can still provide valid and valuable analysis (Knief & Forstmeier, 2021; Micceri, 1989; G. Norman, 2010). The impact of these limitations on interpretation are considered in the Discussion.

Interview protocol

Interview design

Interview questions were aligned to the ER parameters and designed to elicit responses about those parameters as embodied in students' engagement with ERs as a framing mechanism. For example, for the parameter of validity, questions focused on the extent to which stakeholder considerations informed ERs (e.g., Are there any specific activities or methods that you used to develop ERs? Can you give an example of a stakeholder need that was difficult to turn into an ER?). For the parameter of solution independence, questions were designed to understand the generalizability of ERs to potential solutions (e.g., Are any of

Table 1 ER survey prompts and results of statistical analysis: mean (μ), standard deviation (σ), skewness (Sk), kurtosis (Ku), Shapiro–Wilk (SW), and Levene's (L). Prompts were bipolar, 7-point scale, with endpoints named in the question

	Solution Independence (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 design problem?)				Validity (How important or unimportant is it that engineering requirements are based on stakeholder needs when working on a design problem?)				Consequentiality (How likely or unlikely are the engineering requirements to highly constrain a design problem?)			
	Pre		*Post*		*Pre*		*Post*		*Pre*		*Post*	
	FY	SR	FY	SR	FY	SR	FY	SR	FY	SR	FY	SR
μ (σ)	5.37 (1.7)	5.50 (1.73)	5.36 (1.67)	6.05 (1.2)	5.69 (1.4)	5.75 (1.08)	5.50 (1.34)	6.16 (0.89)	5.21 (1.4)	4.8 (1.56)	5.32 (1.4)	5.36 (1.12)
Sk	-1.08	-1.48	-0.978	-1.61	-1.53	-0.861	-1.11	-1.37	-0.945	-0.447	-0.96	-0.779
Ku	0.093	1.23	-0.042	2.79	2.3	1.74	0.971	2.76	0.45	-0.596	0.503	0.99
SW	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.004	< 0.001	< 0.001
L	0.674		0.003		0.268		0.003		0.209		0.128	

your ERs associated with a specific solution concept? At what point did you develop concepts for solving the problem, before or after setting requirements?). Interview questions were adapted to match the context of course assignments.

We anticipated that students might not understand the terminology of ERs, so we accommodated this in the interview protocol. For instance, each interview started by telling interviewees our definition for ERs. Additionally, for first-year interviews, we adopted language from the course (i.e., “metrics” in place of “requirements”).

First-year students were interviewed at three points: 1) after the alternative fuels selection/policy assignment, 2) after the wind turbine project, and 3) at the conclusion of the spring semester and focused on the impact paper. Capstone students were interviewed at two points: 1) conclusion of the fall semester, coinciding with selection of a concept and 2) end of the spring semester, as design specifications, prototypes, and technical reports were being finalized. Each interview was 15–20 min long.

Interview analysis

Interview transcripts of 17 (nine senior and eight first-year) students were analyzed in a two-stage process. First, we conducted discourse analysis, (Gee, 2014) drawing from a previous toolkit that characterizes agency in talk (Konopasky & Sheridan, 2016). The first stage of coding applied the Framing Agency Coding Tool (FACT) (Svihla et al., 2021), in which 80–90% of clauses are autocoded accurately, and human coders resolve remaining clauses, including instances of “you” as an object and specific nouns as subjects (Svihla et al., 2023). Interviews were transcribed verbatim, and each transcript was organized into verbal clauses using an automated script and imported into FACT. This initial coding was used to analyze students’ discourse to understand variability in their agency within these assignments. This initial coding. For example, consider two different ways a student might describe their design project:

- “We weren’t given a problem, we were given a solution. We had to retroactively think of the problem.”
- “We didn’t have a clear problem, and the client wanted a specific solution. We framed the problem to fit that solution.”

In both, the students share agency with their team by using a first-person plural pronoun (“we”). In the former, the students use passive construction (“were given”) and modal verbs showing a lack of control (“had to”) to offload their agency, presumably to instructors or clients. In the latter, they attribute the solution to the client, and use their agency to deliver a problem from the client’s point of view that fits the solution. While there are many other interpretations we might bring attention to, our purpose in contrasting these two comments is primarily to highlight how this agency toolkit foregrounds attention to the subjects of clauses and verbal forms.

After coding with FACT, second-cycle coding considered student responses and the extent to which they offloaded their agency. Through pattern coding (Saldana, 2015), we sought to characterize authentic (i.e., problem-endemic) and inauthentic (i.e., class-constrained) forms of offloading in relation to the three ER parameters. Problem-endemic offloading suggests a constraint on agency that is authentic to practice, while class-constrained offloading may be inauthentic to practice.

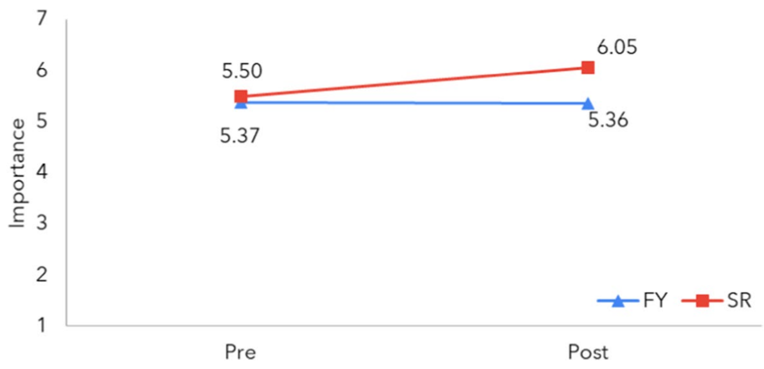

Fig. 2 Pre and post survey response for first-year and senior students related to solution independence

Elisa: Because we didn't know at the beginning, we didn't know what to quantify. We just know that 'Oh, this is the solution, now let's look at some papers that discuss this topic.' [...] So it's concept-first before engineering requirements.

May: Because for our project we weren't necessarily—we weren't given a problem, we were given a solution, and we kind of had to retroactively think of the problem that it would be solving.

Ismael: Within the first meeting, as soon as we got our engineering requirements from Dr. Z, we were coming up with solutions.

John: We developed them after getting our engineering requirements. Like two, three weeks after, we all sat down for initially brainstorming and everyone sat down and turned out like 30-35 concepts of what the thing could look like. It's just little sketches.

High agency marker. First person singular subject
Shared agency marker. First person plural subject
Framing agency marker. Verbs show potential control
Low agency marker. External person/object subject
Low agency marker. Verb indicates lack of control

Fig. 3 Quotes from bioengineering and mechanical engineering seniors, with shading to highlight discourse markers of agency

Val: We identified the solution before the metrics because through our research, we found that with our main, like our front runner was resistance workout machines.

Aaron: We kind of looked at solutions and worked our way backwards so we were like here's all these materials we could use and then our control group was basically common plastics. And then we work backwards from there.

Janelle: Before. I started before and then afterwards- because when I originally built out this project, [the instructors] were like this is good, but you need metrics to measure out the success, so it was more of an afterthought.

Fig. 4 Quotes from first year students about their impact paper, with shading to highlight discourse markers of agency

Toward a credible and trustworthy analysis, triangulation through multiple researchers and data sources was used (Merriam & Tisdell, 2015). Interview analysis was conducted collaboratively by a team that included two student assistants and two design researchers (the authors of this manuscript). Initial coding via FACT was performed by the student research assistants and then reviewed by the authors. This process was iterative, supported by weekly check-ins, reviews, and discussions about refinements, which supported the students to calibrate to the process. The first cycle coding is visible as color-coding in the transcripts shared, making it available for peer scrutiny (Figs. 3, 4, 6, 7, 9, and 10). Second cycle coding involved multiple interpretive cycles with student researchers and the authors, working collaboratively to synthesize findings. Additionally, we conducted member checks with interviewees during second interviews which included consideration of artifacts (e.g., final presentation slides, reports, assignments).

Findings

Findings are organized by ER parameters considered in this study—solution independence, validity, and consequentiality. Results from survey items most related to those parameters are reported and then contextualized through interview responses. Responses demonstrate the variability in agency and (in)authentic offloading of agency. While we analyzed interview responses from all students as part of our analytical process we share select representative quotes.

Solution independence

Survey findings

We found an interaction effect ($F(1, 252) = 2.49$, $p = 0.116$) and within-subjects difference ($F(1, 252) = 2.32$, $p = 0.129$), but these were not significant (Fig. 2). This suggests that neither course had a significant impact on students' perceptions of the importance of maintaining solution independence in specifying ERs. While not significant, we note that seniors showed an increase in importance from pre ($M = 5.50$, $SD = 1.73$) to post ($M = 6.05$, $SD = 1.20$). By contrast, first-years' importance rating stayed constant from pre ($M = 5.37$, $SD = 1.70$) to post ($M = 5.36$, $SD = 1.65$).

Interview findings: seniors

The biomedical engineering seniors (Elisa, Ismael, and May, Fig. 3) tended to describe being given a solution concept or set of ERs, rather than beginning with a problem, a situation that could undermine students' opportunities to develop an understanding of solution independence. This is noticeable in the comments. Elisa shared agency with her team ("we") in discussing her lack of knowledge and positioned the solution as given, and therefore, positioned her team as not using their agency to make choices about the design problem; instead, her discourse here suggests their role was to learn about the solution, and in the process, accept the requirements as set. Similarly, May described receiving a solution and used modal verbs to offload her agency ("have/had to") for framing a design problem. The lack of agency is attributed to meeting a class expectation, rather than an authentic design action. Ismael exhibited shared agency with his team and described authentic practices of concept generation, however, the timeline of concept generation suggests limited practice in framing the problem through the development of engineering requirements.

By contrast, the mechanical engineering seniors (John, Fig. 3) described their experience as one in which ERs were developed before solutions. John's explanation makes unclear who was responsible for developing the requirements, however, we know from

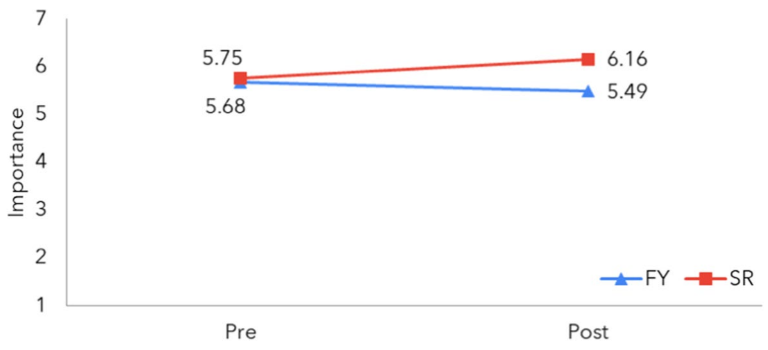

Fig. 5 Pre and post survey response for first-year and senior students for validity

other parts of the interview that his team developed the ERs. His use of a modal verb ("could") suggests an appropriate tentativeness about the solution.

Interview findings: first year

We found no examples where first-year students spoke to solution independence when talking about their work in the fall, when their solutions were constrained to a menu of options from the beginning. However, in their spring project that culminated in an impact paper, their comments offered more insight into their progress on understanding of solution independence (Fig. 4). Like Val and Aaron, the students commonly shared agency ("we") with their team for investigating existing solutions as a starting point. In doing so, they took up roles as finders and evaluators of solutions, a position that could still suggest the need for ERs that are solution independent. However, Val and Janelle both mentioned developing metrics after finding solutions. Even though Janelle described being positioned by the instructors as having agency over the metrics, the post hoc nature diminished their importance to her. Ultimately, the students did not perceive that they had agency over framing the problem through ER development. Rather, they were reliant on existing concepts and the ERs they might imply.

Validity

Survey findings

We found a statistically significant interaction effect ($F(1, 252)=5.28$, $p=0.022$) and between-group difference ($F(1, 252)=4.58$, $p=0.033$). This suggests that the different experiences of first-year and senior students lead to a divergence in opinion from pre to post (Fig. 5).

Inspection of pre/post means shows that at the start of their respective experiences both seniors ($M=5.75$, $SD=1.08$) and first-years ($M=5.68$, $SD=1.40$) had a similar and generally high opinion regarding the importance of ERs being based on stakeholder needs for design. By the conclusion of those experiences, seniors ($M=6.16$, $SD=0.89$) increased their average importance rating and reported less variability while first-years ($M=5.49$, $SD=1.34$) slightly decreased on average.

Alex: The one engineering requirement we had was—doesn't, um, the system can't affect the [skate]board dynamics and, like, there [is] a couple things like [sensor system] size and weight come into that, but also where we mount the sensor. […] We turned that into "It had to have a minimum or maximum footprint, it needed to be small footprint, like less than 36 inches squared and needed to be less than two inches in thickness, and it needs to be less than like 200 grams."

Peter: Difficult was probably, um, weight. When we were talking about our product and how heavy it can be. That played into a lot of things of, you know, we were asking how much people—how much can you comfortably lift to shoulder height.

Ron: It's been useful, hearing from our sponsors because, like they've given us some like landmarks or are just like "Oh, when you like drill into the bone you have this feeling of like puncturing the inner or like outer wall in the hollow cortices and then going into the next wall," so we can't really like make a number out of that, but it's just like a general kind of thing that we have to keep in mind.

Joy: That's a good question. Now that you're mentioning this, because, you know, we have such a short time to work on this, well, you know, we're taking other classes, we try to make this project like super basic, that we didn't think about, you know, all the needs that we should, you know, like also like consider.

Fig. 6 Quotes from bioengineering and mechanical engineering seniors, with shading to highlight discourse markers of agency

Interview findings: seniors

The mechanical engineering seniors tended to explicitly recognize and work through the validation parameter (Alex & Peter, Fig. 6). They started with an approach to framing the process that considered qualitative issues and their transformation to a quantitative frame. Alex both shared his agency with his team ("we") and attributed agency to the problem using modal verbs showing no control ("had to"). In doing so, he foregrounded a qualitative concern that impacts the skateboard rider's experience and thus constrained ERs related to size, weight, and mounting location of the sensor system they were designing, all of which they later refined into specific measures. Similarly, Peter attributed agency to stakeholder needs that he characterized as difficult to convert into specific ER metrics. Peter's tentative talk through use of modal verbs ("can be") also suggests some potential to relax a particular constraint or that his team brought personal experience into the problem to assess its reasonableness. The ME students tended to attribute agency to the problem in ways that are authentic and appropriate to practice.

The bioengineering seniors were more varied in their accounts of accommodating stakeholder needs through specific ERs (Ron & Joy, Fig. 6). For instance, Ron offloaded his team's agency, describing the creation of an ER to represent the qualitative feel of a surgical procedure as something that cannot be measured. It is challenging for designers to use vague guidelines "to keep in mind" when they also have quantified metrics; such guidelines haunt the problem space but may not show up in the solution. Joy's reaction to being asked about ERs and stakeholder needs reveals that she had not given much thought to the issue. Her explanation, shared with her team ("we") situates the work as just another class project to manage among many, constrained by other academic obligations.

Interview findings: first year

First year students' opportunities to consider the stakeholder-ER connection occurred at two points: first within the alternative fuels assignment (Fig. 7, Evan & Tina) and

Evan: It's definitely a little bit challenging to do that, but I mean—so usually what we were told to do is put a one- or two-words statement in the chart there.
Tina: I definitely feel like the metrics that would—that would align to these were a bit difficult to measure, like, for example, um maybe technical feasibility, that, that could be hard to measure, I mean, especially since we didn't have much to go off of.

Aaron: There might have been some, but nothing like I said really sticks out. [...] I mean, a lot of it is data. CO2 emissions—that was one thing—it's not really directly related to the stakeholder.
Tina: Initially the durability wasn't in numbers, but like we had to do research like it was. We pretty much had to make approximations for the life expectancy of the system so that is something.

Fig. 7 Quotes from first year students about their alternative fuels project (Evan & Tina) and their impact paper (Aaron & Tina), with shading to highlight discourse markers of agency

second as part of the impact paper (Fig. 6, Aaron & Tina). Although the assignment in the former tasked them with turning qualitative criteria (e.g., capacity, sustainability) into quantitative ER metrics (e.g., cropland required for ethanol from corn), students varied in their perceptions of this task. For example, Evan offloaded his agency onto the course instructors in explaining how they accomplished the task. Tina's tentative explanation reveals her uncertainty about how to go about turning a qualitative criteria into a quantitative ER metric and perhaps, whether it was their role to do so.

Later, related to their impact papers, students were asked if their research led to identifying specific qualitative issues or stakeholder concerns that had to be converted to ERs. Their responses suggested that this was not the case. Some students described a process wherein ERs were established through research but connection to relevant stakeholder concerns was not clear. Aaron exhibited uncertainty and attributed agency to the situation by using inanimate subjects ("it", "that"); while designers commonly do this as they contend with the realities of materials and their properties, Aaron's discourse in this instance positions the ERs as truths to be uncovered, rather than as the result of designers' agentive work. Further, his comment suggests that the problem frame is initially a quantitative one in which metrics like CO2 emissions are not important to stakeholders. Some students, like Tina, described their efforts to convert stakeholder needs into ERs in ways that suggested offloading of agency onto the instructional context. Her account, laced with modal verbs showing no control ("had to"), suggests she did not understand the purpose of transforming qualitative stakeholder needs like durability into quantitative ER metrics.

Consequentiality

Survey findings

We found a significant within-subjects difference for this item ($F(1, 252) = 5.52$, $p = 0.02$). This suggests that for at least one group, there is a perception that ERs constrain design more than they initially believed (Fig. 8). A paired samples t-test was performed comparing pre/post survey means for both first-years ($M = 5.24$, $SD = 1.37/M = 5.34$, $SD = 1.37$) and seniors ($M = 4.80$, $SD = 1.56/M = 5.36$, $SD = 1.12$). The pre/post change was not significant for first-years ($t(214) = -0.981$, $p = 0.33$) but was significant for seniors ($t(43) = -2.41$, $p = 0.02$).

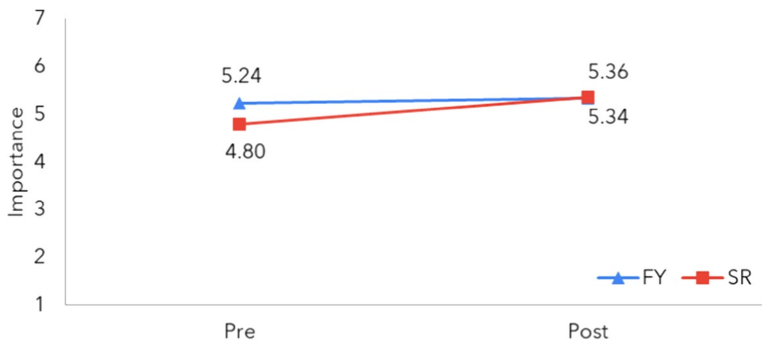

Fig. 8 Pre and post survey response for first-year and senior students related to consequentiality

Joy: I mean, I know that we have to make some tradeoff but it wasn't too many, because, like, our project was very straightforward. It was mostly you know learning how to code, work together as a team, like, learn how to do data analysis and read research papers. […] I know, like, some tradeoff that we had to do along the way, like you know, like, what camera can work better than the other one, um, you know, like.

Ismael: So tradeoffs. This last one right here, allows you to choose 2D and 3D simulation, as you can see these is only two dimensions right? This was a major cutback that we had to do because 3D takes way more time, way more code, and way more processing power, and we were not able to do that in time.

John: We really prioritized like the slope of the roof to keep snow off it. So our requirement of this keeping the snow off the car. We tackle—we did that because we thought it was, it would be easier to come up with a solution for snow and then tackle a hail issue. Probably should have tackled the hail issue first, because that is by the downfall of our design that we made, that it didn't serve good hail protection.

Peter: At a certain point, the feasibility of the design, um kind of took over. […] I was the guy going to be building this and at a certain point, us following the design requirements, as useful as they should have been, um, we got our—we got concepts, like, the chosen concept was things that we couldn't really make, like, I was thinking about it, I was talking with [the shop lead] and we're like I—we do not have the capabilities to do this. So, I pushed the group in the direction that design requirements didn't really point to, you know, as strongly, but I know that we could make.

Fig. 9 Quotes from senior students about their prioritization of ERs, with shading to highlight discourse markers of agency

Interview findings: seniors

Students responded to questions about the prioritization of ERs and how that prioritization impacted downstream design actions. Bioengineering students' responses focused on how they prioritized the scope of project work rather than prioritizing some ERs over others (Fig. 9, Joy & Ismael). For instance, Joy described tradeoffs in terms of project actions, offloading her agency onto the course instructors by using modal verbs showing no control ("have to"). Similarly, in defending their focus on 2D, Ismael offloaded his agency onto the time constraint inherent to the course, which made achieving the 3D functional requirement "way out of the scope." Like Joy, Ismael did not prioritize a particular framing of the problem with respect to the consequentiality of meeting ERs. Such decisions about prioritization focused on the scope of work that they were able to accomplish in the face of course constraints, rather than prioritization of ERs and the consequence thereof.

Jessie: The whole point of this project, I thought, was to find an alternative fuel source that has less of an environmental impact than, um, our current fuel source—coal, petroleum. I prioritize environmental impact over, um, like technical feasibility. So, I personally recommended biodiesel from algae, even though it's not, currently, like, commercially feasible, um, because it has the potential to grow into something that, uh, like, as long as more research is done on it and everything, has the potential to grow, to be more commercially feasible.

Evan: If you can't make it or if you can't make enough of it then you can't use it. [...] In the real world, what would be—what could you actually do, and then, what would be best.

Tina: It was mainly the ones that I felt like I could like, it would be very easy for me to elaborate on.

Janelle: I feel like the way how I prioritize is based on how much information it gives. Vulnerability and stability, you can find a lot, so you don't have to prioritize it as much, but I feel like you have to look really in depth for like technical feasibility, in that sense

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Tina: We decide to prioritize energy output, because, well, at the time we knew that there was, like, a competition to see like who had the most energy output among all the labs, so that was something that we definitely thought about

Evan: We definitely pri- pri- prioritized how much power we made. That was the one thing we went for. We didn't really care about wind down or I mean cut off or cut on speed, because those didn't matter to us. We were going solely to make as much power as we could and we—we just did that by doing what we could by changing whatever we—we can. [...] It was ultimately the one that was deemed most important by what we thought that they wanted.

Fig. 10 Quotes from first-year students about their alternative fuels project (Jessie, Evan, Tina & Janelle) and their wind turbine (Tina & Evan), with shading to highlight discourse markers of agency

Mechanical engineering students' responses on the other hand reflected an understanding of consequentiality of ER prioritization (Fig. 9, John & Peter). For instance, John connected his team's prioritization of slope to a downstream design consequence. In explaining this, he shared agency for the decision with his team ("we") and displayed some tentative uncertainty about their choice to prioritize it ("would," "should"). Peter described a tension between prioritizing ERs to direct their solution and the feasibility of producing a prototype. He shared agency with his team over developing the ERs and offloaded their agency when developing the solution was not feasible; in turn, he showed high individual agency for redirecting his team. His response suggests that he recognized a framing of the problem as represented in the ERs developed by his group that could not be accommodated in their prototype due to constraints on available manufacturing capability.

Interview findings: first year

First-year students reflected in varied ways on prioritizing ERs in their alternative fuels project (Fig. 10, Jessie, Evan, Tina, & Janelle) and their wind turbine (Tina & Evan). For example, Jessie used a generic statement ("The whole point…") to situate her high agency in her prioritizing of an ER that rendered her choice not economically feasible, meaning she recognized a specific consequence of her prioritization. Other students, like Evan, faced with this same tension, dismissed such fuels because they prioritized commercial feasibility; in doing so, Evan also used a generic "you," offloading his agency in a way that prioritized economic viability over environmental impact. He then showed a more tentative stance, using modal verbs ("would," "could") in explaining why feasibility mattered when making decisions about which ERs to prioritize.

In contrast to Jessie and Evan, Janelle and Tina described prioritizing related to their efforts to find information, with Tina explaining—tentatively—that she prioritized what would be straightforward, while Janelle described prioritizing her efforts on difficult-to-locate information. Their accounts suggest an everyday understanding of prioritization, and that this prioritization was driven by the need to balance schoolwork, rather than being driven by the need to frame a design problem.

Later, in explaining prioritization in their wind turbines, most students prioritized a single measure, power output, even though the turbine project includes multiple design factors. For instance, although Tina and Evan both shared agency with their teams over prioritizing energy, they also attributed this prioritization to the course, describing a competition or a sense that the instructors expected this focus. While some students did describe attending to other potential requirements, such as exploring the impacts of various materials or focusing on run time, these were in service of increasing power output. In turn, this narrowed requirements focus may undermine important learning as it relates to making tradeoffs among multiple requirements, as is typically the case in design.

Discussion

We synthesize quantitative and qualitative findings in revisiting our research questions: To what extent do student perceptions about engineering requirements change with design education? What agentive roles do students take in developing and using engineering requirements to frame problems?

We discuss aspects of undergraduate experiences that are foundational and that may serve as barriers to learning about engineering requirements and students' agency over problem framing. We consider this synthesis first in the context of the ER parameters and then more generally in the context of engineering curricula.

Solution independence

Both capstone courses necessitated the development of requirements as an explicit activity, and one that would typically precede concept development. This was the case for the mechanical engineering course, where solution independence was most strongly evidenced during interviews. Their capstone course activities were scaffolded such that they elicited stakeholder needs and specified engineering requirements before developing concepts. Thus, these students appeared to understand and take up the concept of solution independence, for instance, as demonstrated by one student who indicated that he thought of possible solutions almost immediately and before developing requirements but who also wanted to be clear that he "didn't write them down because I didn't want to influence stuff early on." He explained that he understood that setting requirements prior to establishing solutions is important to avoid biasing the problem frame. This demonstrates the solution independence pathway (Fig. 11).

However, in the biomedical engineering course, students were given concepts and solution ideas by their instructors or clients before or simultaneous to framing activities, which undermines the solution independence pathway. Instead, we found evidence for a solution-first pathway (Fig. 11), prior to developing requirements. Biomedical engineering seniors were more variable in their responses and generally less attentive to this parameter.

Similarly, the first-year students followed a solution first pathway, prompted by course activities that tended to offer constrained solution spaces (Fig. 11). Scaffolded by an engineering process model (Fig. 1) similar to the capstone courses, the emergence of requirements (metrics) comes in the "compare alternatives" stage, after "generate alternatives." Across assignments, first-years either did not have agency over setting requirements (i.e.,

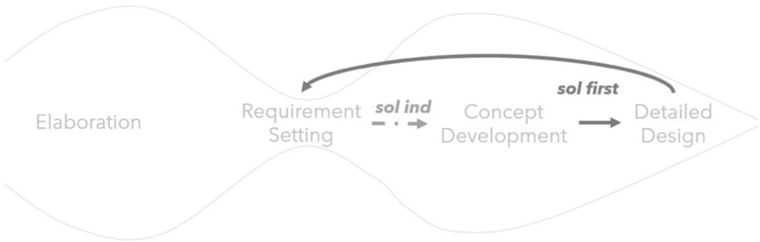

Fig. 11 Solution independence pathway versus observed solution-first pathway in the design process

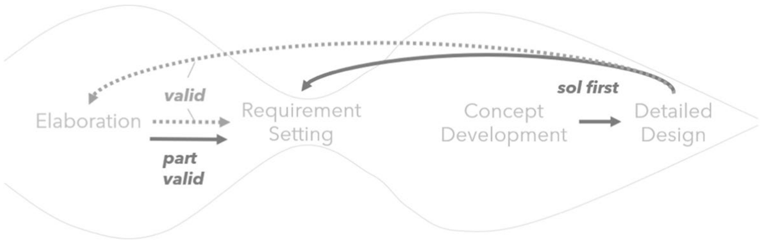

Fig. 12 Validity pathway versus observed partial validity and solution-first pathways in the design process

alternative fuels and wind turbine requirements were set by instructors) or described a tendency to find existing solutions as a basis for problem framing (i.e., impact paper). As course activities were not scaffolded to foreground ERs as a solution independent framing mechanism, there was no apparent growth relative to this parameter. In this regard, the first-year course differs from the design process in important ways that may not support recognition of solution independence.

Consideration of solutions prior to development of requirements within course activities may reinforce a tendency among novice designers to seek solutions before understanding the problem (Crismond & Adams, 2012; Silk et al., 2021; Svihla et al., 2021). This tendency was not disrupted for first-year students, and perhaps not sufficiently for biomedical engineering students.

Validity

With scaffolding, some seniors showed evidence of the validity parameter. Mechanical engineering seniors performed intentional work that began with eliciting stakeholder needs and deriving a set of requirements, inclusive of specific measures, as previously described. Their design efforts foregrounded stakeholder considerations – important to developing high quality requirements (Mohedas et al., 2015) and meeting stakeholder needs (Mohedas et al., 2023) – and established the fundamental basis for validation as part of the initial problem framing. In doing so, they established traceability of stakeholder needs in moving from elaboration to requirement setting in the design process, but seldom moving from detailed design back to elaboration to validate their solutions, thus following the partial validity pathway (Fig. 12).

While not grounded in elicitation of various stakeholder needs, biomedical engineering seniors had regular interaction with a project sponsor. As a stakeholder and proxy for other stakeholders (i.e., patients potentially affected by the design), project sponsors serve as a critical and regular feedback loop by which validation is tacitly reinforced. For some, this provided an opportunity to follow the partial validity pathway. However, the variability in responses for biomedical students suggests that this feedback loop might be strengthened if requirement setting, through establishment of specific measures, were an explicit deliverable. This would mitigate the need to maintain vague guidelines by establishing metrics that can be traced from more subjective stakeholder considerations.

By contrast, first-years exhibited no growth as it relates to the validity parameter, instead following the solution-first pathway. Their explanations made it difficult to know to what extent they understand how to derive ERs that reflect subjective issues that matter to stakeholders. First-years' discussions about ERs as accommodating stakeholder needs suggests that the parameter of validation is not well practiced. ERs appear to be something that are implied by existing solutions (impact paper) or that are provided by the problem statement (alternative fuels). In this way, first-years may have or perceive little agency over framing the problem through a process that starts with qualitative considerations before transforming to quantitative representations of those considerations.

By starting with ERs or solution principles, students may not recognize the role of stakeholders in the ways that their senior peers did. This contention aligns with the work of (Atman et al., 1999) who found that seniors did more work to understand and frame design problems than first year students. Similarly, (Crismond & Adams, 2012) delineate differences between "beginning" and "informed" designers, noting that beginners tend to skip framing and move right to solving, assuming the problem is better defined than it is. In this study, we found evidence that supports this contention but also a more nuanced argument regarding the potential role of structured design processes as a scaffold that support more informed actions, if they are properly reinforced. Where such enforcement is lacking, even seniors may assume the problem is well framed, as we saw with biomedical engineering students. Scaffolding of information gathering behaviors detailed by (Loweth et al., 2022) might better support students in stakeholder engagement and requirement development practices. Integration of UX and/or human factors/ergonomics methods (Canziba, 2018; Spirochkin, 2023; Wilson & Sharples, 2015) may be particularly useful in the biomedical context, and generally represents an opportunity for engaging undergraduate engineers in framing of design problems to incorporate the varied concerns of stakeholders most impacted by the potential solution.

Consequentiality

Seniors demonstrated understanding of consequentiality, though they did not always present consequentiality as a function of their agency over ERs. This was true of biomedical engineering students, who tended to describe consequences in terms of tasks, work scope, and functional requirements. By contrast, mechanical engineering students described prioritization of ERs and the extent to which they accommodated that prioritization in terms of consequences of meeting (or not) ERs. In this way, mechanical engineering students appear to have better traced the consequential pathway (Fig. 13) as compared to their biomedical engineering peers.

The variability in expressed agency and focus on work scope among biomedical students might be mitigated if their navigation of the design process more authentically integrated stages of elaboration and working with (client provided) solution principles. Requiring students to critically evaluate sponsor suggested solutions through the lens of

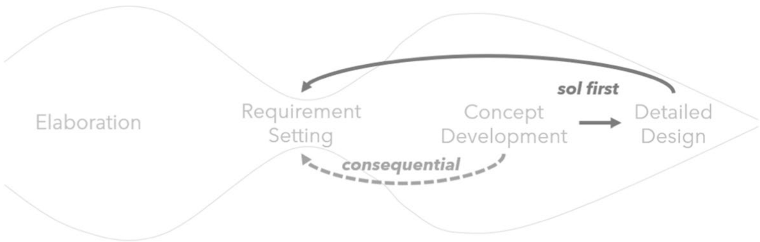

Fig. 13 Consequentiality pathway in the design process

functional requirements, ensuring that they trace the consequential pathway, may support a stronger sense of problem-endemic consequentiality, rather than a course constrained scope of work.

First-years demonstrated a general understanding of consequentiality as in prioritizing ERs through their interview responses about the alternative fuels and impact paper scenarios. In contrast to seniors, these projects were abstract scenarios where first-years recognized the consequences on design outcomes in principle, thus tracing the consequential pathway, but did not tangibly experience requirement derived constraints on their design decisions.

While the wind turbine is a prototype build that should presumably provide tangible experience with constraints, students did not describe working within a requirements framework representing the consequential pathway. Instead their efforts were to achieve a functioning turbine and maximize the power output. They prioritized satisfying their perceptions of what matters to being successful on the project according to instructors. In this regard, a hands-on design experience that could be foundational to understanding ERs and their consequentiality appears to hit a barrier, perhaps hiding latent lessons related to design tradeoffs. Their design experience, as currently scaffolded, does not engage the early stages of the design process, where agency over the problem frame requires the production of requirements that constrain design decisions and necessitate tradeoffs.

Synthesis and implications for design education

Toward synthesizing our discussion for design education, we consider two implications for design education generally, and engineering education specifically: engineering education in the middle years and iterative, recursive (re)framing in design scenarios.

Engineering requirements and the middle years

Survey findings generally showed that students made few gains (Figs. 2 and 5) with respect to their understanding of ERs during the middle years. In some cases (e.g., Fig. 8) there may be a regression in students' recognizing ERs as a problem frame through which to make tradeoffs in downstream design decisions. This illustrates how repeated engagement with well-structured, class-constrained problems shapes students' perceptions of their roles as designers and may reinforce a resilience regarding design beliefs that capstone courses alone cannot disrupt (Leonard et al., 2023).

As the middle years of engineering degrees typically focus on technical content through disconnected courses (Lord & Chen, 2014), there is little room afforded to cultivating students as designers. Most middle years courses include situated scenarios where the pre-existence of a concept and a focus on use of specific theory limits their exposure to pathways that transition from problem framing through problem solving. Often, the concept is an abstraction of a system or component (Bucciarelli, 1994) engaged through a well-structured, plug-and-chug problem (Jonassen, 2014). The pathway they experience in such courses is often limited to detailed design that references requirements that they have no part in setting. Thus, students may come to see themselves as problem solvers, restricted to technical work to refine and finalize the design of pre-conceived concepts, but not as problem framers, who have agency to set the problem through requirements (Svihla et al., 2021).

There is a need to provide students with more opportunities to navigate the full process, spanning the framing-solving continuum, during middle years courses. Those opportunities could be reasonably afforded by adapting current problems to be less well-structured (Olewnik et al., 2022), such that students participate in framing of the problem through requirement setting, rather than allowing the problem frame to be class-constrained.

As many design fields involve the development and use of requirements, future studies and practitioners may look to other design fields for additional guidance on teaching requirements. For instance, in software development, the journal *Requirements Engineering* publishes papers on educational interventions and outcomes. Likewise, faculty may draw upon design methods detailed as part of UX.

(Re)framing and the iterative and recursive nature of design

Design education, even in year-long, client-sponsored design projects, seldom provides opportunities for students to frame problems iteratively. Instead, students' actual navigation of the design sequence is linear. Even when there are apparent opportunities for iteration that might suggest the need to reframe the problem, students instead retrospectively establish the frame as given (i.e., "retroactively think of the problem that it would be solving"). In doing so, they yield their agency in ways that are not problem-endemic. That students yield agency and accept the problem frame as immutable might explain, in part, why students' downstream design work (e.g., unintentional use of prototypes (Deininger et al., 2017)) appears disconnected from the real problem. In such cases, students are not using their agency to direct the co-evolutionary nature of framing and solving (Dorst, 2019), a process that might lead to identification of new and respecification of existing requirements.

Two implications stem from this issue. First, there is a need to better support students in their understanding of the origin and flow of information within the design process to reflect parameters like validity and consequentiality. More than providing process models, a reflection on those processes may be necessary to build and reinforce appropriate forms of framing agency that align with the iterative nature of design.

The second implication relates to scoping of project work. Based on this study, it appears that, at times, the scope of what students are trying to deliver is unrealistic for a one or two semester project carried out by novice designers. Rather than focusing on a subsystem or component, they attempt to solve the problem at the system level. This places students in an unrealistic scenario wherein they "run out of time"—a phrase that suggests a lack of agency.

This suggests a need to support students to use their agency to both frame and *re*frame the problem, perhaps at the level of a subsystem or more narrowly scoped—yet still open—problem. This is necessary to allow them sufficient time to meaningfully solve part of the problem that can be situated within a system level problem frame. In this way, recursive framing—considering the subset of system requirements that get passed down to a subsystem under consideration (NASA, 2007; Walden et al., 2015)—may be educative and support forms of agency that govern the scope of work in ways aligned with practice. A recursive design perspective supports reframing of problems at different scales, allowing designers to solve interconnected design problems within the same system (Barba, 2019). Additionally, it would provide a better opportunity for students to fully engage the iterative process of framing and solving.

Limitations

We note three limitations of this study. First, we are missing some pieces of what students may be able to do and understand as it relates to requirements since we used a clinical interview process rather than an ethnographic approach. While clinical interviews can yield valuable insights, our understanding is limited to student perceptions that may differ outside of situated practice (diSessa, 2007). In future work, we need to situate data collection within the problem engagement discussions of students to see if reflections on learning differ from enacted behaviors.

Second, our survey is exploratory and thus there are opportunities for a more robust assessment of student perceptions about developing and working with ERs. While we expected and found data that were somewhat skewed—in common with most survey data—we collected data from a single institution. Further studies can confirm the data structure through additional cross-site data collection. Further, we need additional ways to measure student understanding of engineering requirements (e.g., origins, development, constructs that make them useful within different problem contexts). This study used an exploratory survey linked to requirement parameters derived from literature, but additional research is necessary to refine and validate these constructs.

Finally, more research is needed on the tools and methods used for elaboration and requirement setting, and across disciplines. Understanding the ways in which these methods might systematically vary by discipline is important to research design that is better able to investigate the differences in engineering educational environments that map to disciplinary practice. In other design fields, especially those that depend less on bringing together qualitative and quantitative information, the roles of requirements and the practices used to develop them may differ.

Conclusion

This study used quantitative and qualitative data to explore first-year and senior students' growth and understanding of engineering requirements as a mechanism for framing design problems. Through statistical analysis of survey data we considered student learning related to requirements through ER parameters of solution independence, validity, and consequentiality. Through discourse analysis of retrospective interviews we explored the variability in students' framing agency in design-related assignments. Our findings suggest that students' learning about the role of requirements as an important mechanism for problem framing and their agency over that framing is undermined by pedagogical structures that occur within the first-year and senior capstone courses themselves. Further, findings support a conclusion aligned with prior research that the engineering curriculum during the middle years does not support students' development as designers capable of both framing and solving problems, despite its recognized importance in practice and by accreditation bodies. This work provides additional support for calls to reform engineering education across the curriculum in order to better prepare students for realities of practice, including their roles as designers.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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