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A Systematic Review of the Literature on Engineering Requirements and the Framing of Design Problems in Engineering Education

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Introduction and Research Purpose

While a great deal of literature has focused on other aspects of engineering design, especially related to teaming, problem solving, and ideation, less attention has been paid to problem framing, and especially to the setting of requirements. With reference to design texts and sources, we define engineering requirements (ERs) [1–6] as a set of solution independent, valid, and consequential parameters that describe the capabilities and behaviors of a system necessary to meet stakeholder needs and expectations; and represented by a metric and a target value.

Understanding how engineers set requirements as part of problem framing is important because it is the key way in which they contend with both quantitative and qualitative stakeholder needs and contextual constraints and factors, while recognizing that some requirements are tentative and contingent upon the potential solution paths. As such, requirements should be approached abductively, yet they are sometimes represented—in textbooks and resources—as identified through rational deductive (and sometimes inductive) processes [7]. One reason that inductive and deductive reasoning are inadequate is that design problems are ill-structured and do not, at the outset, contain all the information needed to reach a satisfactory solution. We employ Dorst's frameworks on determinedness [8] and abductive reasoning [9] in design to understand this situation. From the perspective of determinedness [8], some information, often known at the outset or uncovered early, is determined, meaning it is factual, knowable, and can be shown to be accurate or not. Next, some aspects of the problem are underdetermined, meaning they are open to interpretation by the designer, who works tentatively to test ideas for their fit with the problem. Finally, some aspects of design problems are undetermined, meaning they are not resolvable using inductive or deductive reasoning, but are subjective, and decided by the designer based on their experience, judgment, and preferences. This requires abductive reasoning on the part of the designer and is essential to setting an appropriate problem frame that contends with a co-evolving [8] value proposition and solution path [9].

In this systematic review of the literature, the extent to which design engineering education experiences provide opportunities for students to participate in this abductive reasoning process is of particular interest.

Background: Other Literature Reviews

To frame our work, we conducted a search to investigate existing reviews. We identified very few systematic or scoping reviews. Those relevant to the current study have primarily focused on the fields of computing/software engineering, where requirements engineering has a more consistent, and arguably straightforward role within practice. Most such studies have been published in the journal *Requirements Engineering*, "a multi-disciplinary journal focusing on the elicitation, representation, and validation of software-intensive information systems or applications."

For instance, a recent software engineering review categorized 152 papers published prior to 2020 by metadata (e.g., author, keywords) as well as paper type (e.g., validation, evaluation, philosophy), setting, and contribution (i.e., Metric, Tool, Model, Method, Process, Other) [10]. They found that most papers proposed solutions or reported author experiences, with most contributions classified as method or other, leading them to characterize research on requirements in terms of “low maturity of the field” but also suggesting that the existing research spans “a diverse set of contributions and solution avenues exist to teach RE, thereby suggesting a rich (albeit unsystematic) ‘toolbox’ of educational approaches” (p. 157). Similarly, another review identified that most papers focused on requirements education in software engineering reported on a method for teaching [11].

A 2015 systematic review of requirements education also within the field of software engineering reviewed 79 papers published between 1995 and 2012 [12]. Over half of these papers did not report empirical studies. A majority reported studies on methods and tools for doing or teaching requirements. The review summarized feedback for teaching requirements engineering based on the results and implications of the papers they reviewed; specifically, they suggested supporting students to define the problem scope, to be specific rather than vague in their requirements, to review existing tools professionals use in working with requirements, as well as involving students in all aspects of setting and working with requirements, including exposing them to failures in this process.

Thus, based on the existing papers reviewing research on requirements, there is a need for additional work beyond the software engineering field to characterize research on requirements setting, especially in engineering design education.

Framework

Design necessitates abductive reasoning in order to ultimately determine both the value proposition and the solution principle (form and function) [9]. Though it may appear an informal cognitive style of design thinking [13], the process underlying this form of reasoning among professional designers is a deliberate exploration of the problem space toward uncovering emergent themes that establish a problem frame [9]. Within the realm of engineering practice, this deliberate exploration is typically formalized as engagement with stakeholders to understand both quantitative and qualitative needs and concerns, which in turn are translated to a set of engineering requirements and possible solution paths. We contend that the establishment of requirements is a crucial form of problem framing, a tenuous output of abductive reasoning that allows engineers to resolve under- and undetermined facets of a design problem as they work to realize a solution.

In this regard, design is inherently interpretive and imparts a few important considerations in the setting of requirements [8]. First, it is important that designers make their interpretation of the problem explicit, and establishment of engineering requirements provides one such explicit representation of the problem; one that can be negotiated with stakeholders throughout the design process. Second, designers may need to set (tentative) requirements based on subjective appraisals and preference assessment to resolve uncertainty in the problem. Such tentative requirement setting provides structure to the problem, while still allowing for negotiation of requirements (and solution principles) with stakeholders. Third, in recognition of subjectivity in design decisions – some of which are engendered by negotiable, tentative requirements – design necessitates a reflective approach (i.e., reflection-in-action [14]). Reflection is at the heart of design iteration, as it encourages designers to evaluate design decisions relative to established requirements, which leads to not only revision of the solution but also reframing of the problem (e.g., updating requirements in negotiation with stakeholders).

In recognition of calls for more design-based engineering experiences [15], engineering education has included more design within the curriculum. However, the inclusion of design-based experiences may not always engender important facets of design practice because they short-circuit the need for abductive reasoning. Abductive reasoning is important to both solution generation [16] and framing actions like the setting of engineering requirements and necessitates agency over both. That agency is shared with other stakeholders and objects across a range of design practices [17]. Educational experiences that focus on methods or isolated stages of design may lose important context in ways that undermine design learning [17]. For example, students who tend toward prescribed design practices (e.g., rigid, predetermined requirements), may not develop in terms of the thinking and skills important to the holistic and integrated nature of design [18]. Similarly, engineering education as currently experienced has been found to decrease students' self-perceived design thinking ability, particularly as it relates to incorporating feedback from others [19].

There is reason then to engage students in the full range of design practices, including problem framing through the setting of engineering requirements, and affording them with the necessary agency to fully experience that messy practice. Framing agency – making consequential decisions to frame ill-structured design problems as part of a learning process [20, 21] – is important to the development of abductive reasoning abilities for successful design. Understanding the extent to which students may have framing agency in the process of setting engineering requirements is of fundamental interest in this study.

Methodology

We conducted a systematic literature search according to PRISMA guidelines [22]. Initially, we included studies of ERs conducted in any setting, including research and industry. While such settings may depict how professionals treat ERs, our focus in the current study was to investigate the treatment of ERs in education settings. We therefore posed research questions to guide this work:

- What characterizes the distribution of engineering education research literature that describes engineering requirements, in terms of:
  - Publication frequency over time?
  - Academic standing of participants?
  - Field/discipline of study?
  - Research methods?
- To what extent does this literature depict students in agentive roles, responsible for framing abductively and setting requirements? And, does this vary:
  - Over time?
  - By academic standing?
  - By field/discipline of study?

We used the following terms, limited to title and abstract: designer or engineer; undergraduate, industry, or workplace; and "engineering requirements," "design requirements," "technical specifications," or "design specifications." Journals and conference proceedings were included. Our primary database was Engineering Village, but we conducted a follow-up search in the ASEE PEER database. Our search resulted in 8042 results. We imported these citations into Covidence software (https://app.covidence.org/), which removed duplicates and supported two independent reviewers to assess each citation (Figure 1). To address the research questions, we applied additional exclusion criteria to focus the set on educational settings. Future studies will revisit the studies that are set in industry or research settings to investigate how such settings report on ERs. The current study focuses exclusively on those papers set within educational settings, resulting in a set of 80 papers.

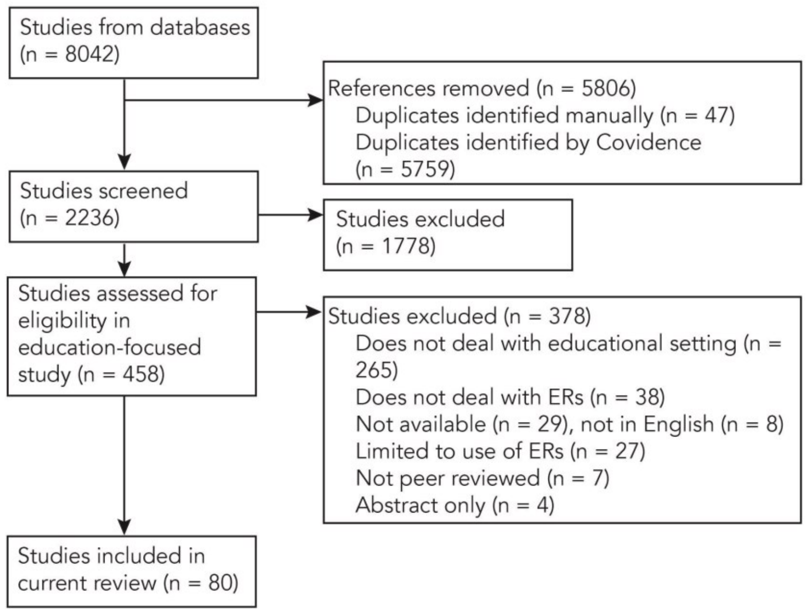

Figure 1. PRISMA chart of review process

We conducted a screening review of titles and abstracts to identify papers that met our criteria. We then located full text copies of the papers and began a full text review. During the full text review, we made notes for the papers as a means to track developing insights about the set. These included initial insights about the qualitative-quantitative transition, abductive reasoning, determinedness, and who was responsible for setting the requirements. We then reviewed these notes to generate an extraction tool within the Covidence software. This fully customizable template allows scholars to decide what information they want to extract from each paper, supporting initial analysis. In our prior use of the software, we discovered that the extraction tool, when subject to consensus across independent reviewers, requires perfect agreement, even down to the spaces between words. We therefore elected to iteratively review and discuss a subset of papers together, allowing us to refine the extraction tool such that most information could be easily identified without relying on consensus (Table 1). This, however, meant that more interpretive analysis is needed as a follow-up step. We therefore conducted a qualitative, critical meta-synthesis [23] of the set of papers.

Table 1. Framework for analyzing papers

<table>
<tr><th colspan="2">Description</th><th>Options</th></tr>
<tr><td>Are ERs subjective and developed by humans?</td><td>Using Dorst’s (2004) framework, design includes

(a) Determined (unalterable requirements);

(b) Underdetermined (work to make ERs);

(c) Undetermined (judgment, subjective).</td><td>Induction/Deduction (information treated as objective, process as deterministic; may focus on determined aspects or seek to automate or remove bias from underdetermined aspects; excludes undetermined aspects)

Abduction (some information treated as subjective; may include determined, underdetermined, and must include undetermined aspects)</td></tr>
<tr><td rowspan="2">General characteristics</td><td>What other attributes describe the paper?</td><td>Qual/quant transition
Math, code, automation, fuzzy
Other</td></tr>
<tr><td>In educational studies, are students responsible for developing ERs?</td><td>Instructor/curriculum gives requirements
Students develop requirements
Unclear</td></tr>
<tr><td rowspan="2">Participants, setting, field</td><td>Paper setting</td><td>Educational
Industry
Research</td></tr>
<tr><td>Field</td><td>Field (e.g., CS, ChemE, etc.)</td></tr>
<tr><td>Methodology</td><td>NOTE: Count human subjects (e.g., interview, survey, SME) if mentioned, even if little data or methods described</td><td>Human subjects data
Analysis of literature, standards
Analysis of materials, conditions
Math, code, automation
None or unclear
Other</td></tr>
<tr><td>Results</td><td>Are outcomes/results reported for...</td><td>Learners
Curricula
Stakeholders
Other humans
Things/products
Standard(s)/requirement(s)
Processes/methods
Math, code, automation
Other</td></tr>
</table>

Results and Discussion

Characterizing the paper set

Overall, we found that the number of papers that reported on ERs has increased over time (Figure 2), with a decrease in the final period. This decrease might be attributed to the COVID-19 pandemic. Specifically, many studies during this period focused on pandemic impacts on instruction, and instruction changed during the pandemic, which may have resulted in changes in how design was taught.

Most papers reported on studies in general, multi- or interdisciplinary (26%), other (21%, mechatronics, agricultural, software, etc.) or mechanical (28%) engineering. Next, several papers reported on studies in aerospace (11%) or electrical (11%) engineering. Finally, few papers reported on studies in biomedical (6%), civil (5%), or chemical (3%) engineering. A majority of the papers included seniors (51%), followed by sophomores and juniors (39%) and first-year students (23%); 11% did not specify beyond describing the course as an undergraduate course.

The majority (93%) of papers reported in some detail on curricula or programmatic experiences, yet these seldom provided much information about students' experiences. In terms of what the studies reported, 55% included human subjects data and 54% reported conclusions about learners; note that two papers shared human subjects data but made no conclusions related to learners and one drew conclusions about learners despite sharing no human subjects data. Thus, slightly less than half of papers did not report empirical research, and very few described a methodology in alignment with educational research, instead sharing anecdotes and instructor observations. Overall, this limits our understanding of both the reasons behind instructional designs as well as the impact they have on learners.

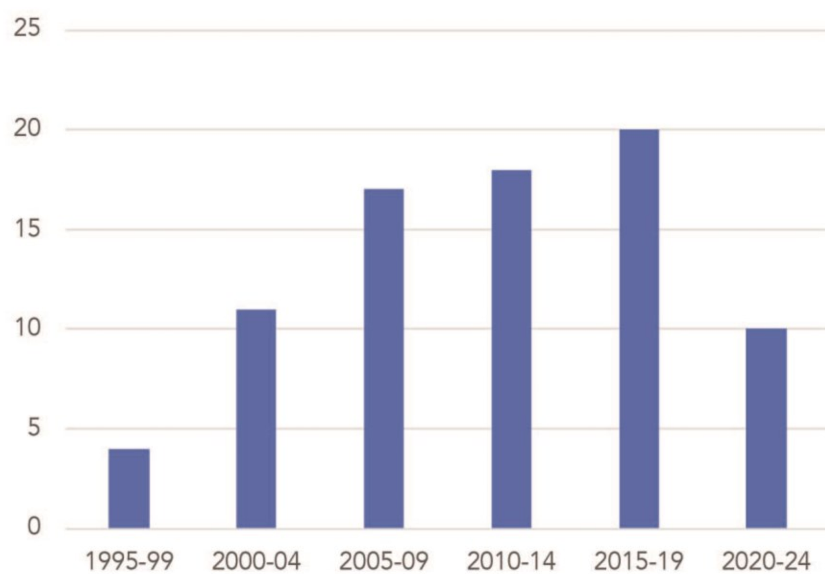

Figure 2. Frequency of papers in sample by five-year periods. Note that the final period, 2020-2024, is incomplete as the data did not include papers from the last 3 months of 2024.

Understanding students' roles in design learning experiences

Overall, 48% of the papers described abductive design and in 55% of the papers, students were at least partially responsible for setting the ERs (Figure 3). Note that some studies included multiple courses, spanning, for instance, first-year and sophomore students. We conducted chi square comparisons, but found no significant differences by academic standing in terms of whether students received abductive design or set ERs themselves. However, within years, we did find significance. Specifically, first-year students were more likely than not to receive abductive design, $\chi 2$ (1, N = 80) = 5.69, p = .03, as were senior students, $\chi 2$ (1, N = 80) = 4.12, p = .048, while students in the middle years were not, $\chi 2$ (1, N = 80) = 0.11, p = .82. These trends are generally likely the result of classes in the first-year and senior year that focus specifically on design, whereas in the middle years, design is more commonly an add-on to a technically focused course. Similarly, first-year students were more likely than not to be responsible for setting ERs themselves, $\chi 2$ (1, N = 80) = 4.87, p = .03. However, this was not the case for either seniors, $\chi 2$ (1, N = 80) = 4.00, p = .07, or students in the middle years, $\chi 2$ (1, N = 80) = 0.81, p = .49.

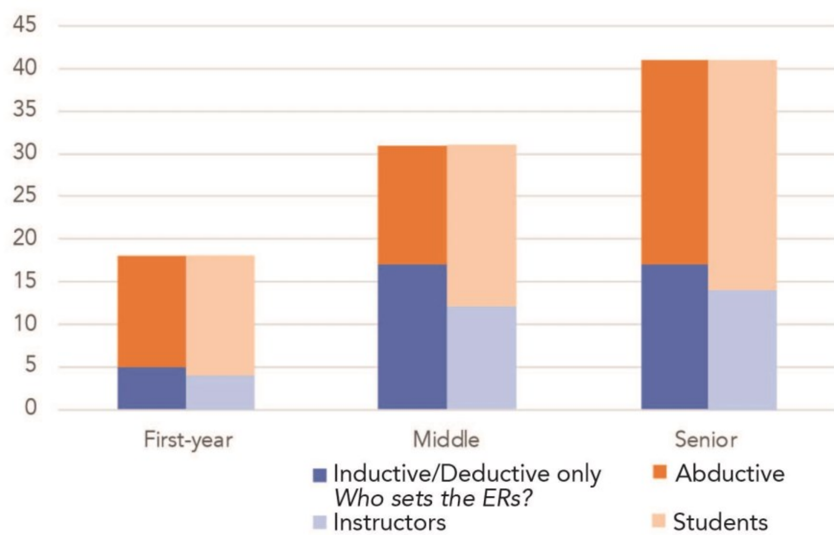

Figure 3. Number of papers addressing ERs by academic standing, grouped by whether the projects included abduction and whether students were at least partially responsible for setting the ERs.

Within first-year courses, service-learning is a common approach that supports abduction. For instance, first year students proposed vertical planter designs for the community [24]. They interacted with stakeholders to understand needs related to climate, preferences, and yield, then used these to set ERs. While they did not have the option to dramatically reframe—they were constrained to creating vertical planters—the wide variety of design solutions proposed demonstrates that the problem was still ill-structured. However, in many cases, iteration did not seem to lead to refinement of ERs, which would limit traceability/evaluation through validation and verification stages. The variety of material possibilities also suggests an abductive approach. The authors conclude with guidance, including the importance of emphasizing social aspects of the project. Indeed, for first year design projects, when students may have highly varied background experiences and limited technical knowledge, sociotechnical projects still provide accessible ways to gain experience with framing design problems. Likewise, in another first-year service-learning course, students framed problems based on their interactions with stakeholders—teachers and students in an elementary school serving many students with disabilities [25]. The variety of projects, from lesson plans to fidget chairs, demonstrates the ill-structured nature of their design work. While limited detail is shared about how students set ERs, pre/post measures suggest that doing so helped students, and in particular, the women, make gains in their design self-efficacy.

Some studies treat setting ERs developmentally or otherwise suggest that students cannot set their own ERs prior to completing significant technical coursework. For instance, in a study of a junior and senior design sequence, the juniors are given the same problem, although it is ill-structured as their design solutions are varied. In senior year, they work with a client to identify and address client needs. Thus, it is an increasingly abductive process [26].

In a study comparing two different approaches to teaching a high-enrollment sophomore software engineering course, the authors identify a key tension between instructor control over specific conceptual learning and the higher student agency needed for them to learn to direct requirements setting [27]. This is a key issue in courses that sit within the middle years of engineering programs, where a focus on technical knowledge acquisition can stand in the way of learning engineering practices. We argue that this dichotomy – between engaging in high agency versions of engineering practices and gaining technical knowledge – could be resolved in such courses: first, if a problem can be more tightly constrained yet still ill-structured, this can focus students on certain topical areas; second, grading can emphasize the process rather than the final products.

We found differences by field in the degree to which the design experience was abductive (Figure 4). A majority of general, interdisciplinary, and multidisciplinary (57%, 12 of 21), biomedical (80%, 4 of 5) and other (65%, 11 of 17) engineering courses described abductive design. One of the two chemical engineering courses (50%) described abduction. In contrast, fewer than half of the aerospace (33%, 3 of 9), electrical (18%, 2 of 11), and mechanical (45%, 10 of 22) engineering courses did so. None of the four civil engineering courses described abduction.

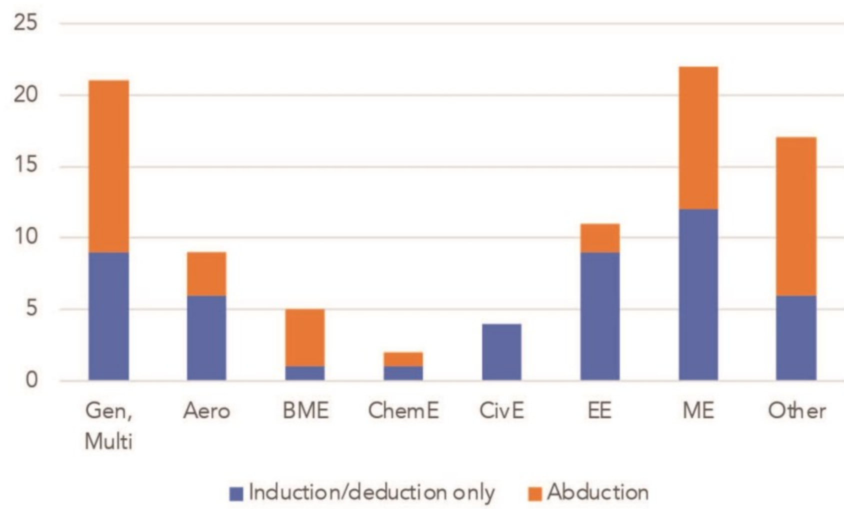

Figure 4. Number of papers by discipline, providing abductive or inductive/deductive only experiences.

Implications and Limitations

Our finding that few papers used systematic educational research methodologies has implications for future research. First, authors, if not familiar with such methods, may seek out collaborations with education researchers, learning scientists, or educational psychologists. Alternatively, they may instead report on their instructional designs in more detail in a "design case" [28–30]. This genre provides a vivid and vicarious account of how and why someone designed a learning experience. Such accounts are useful for others because they detail the particular context and reasoning, allowing others to make informed decisions about how to adapt an instructional design for another situation.

Most of the papers in our set focused on design education broadly or on more commonly-studied aspects, like teaming. Thus, many papers in the set were difficult to accurately assess in terms of students' roles in setting ERs and directing the problem framing process. This is further hindered by prevalent use of passive voice, which sometimes obscured whether instructors or students were responsible for setting ERs. Based on this, we encourage authors to adopt active voice and to specify more clearly students' roles in their design education, and in particular, how much agency they have in problem framing.

Finally, in recognition of the abductive reasoning often required in design, there is an argument for explicit incorporation of reflective practice in design education experiences. This metacognitive activity is important to the iterative negotiation necessary to co-evolve the problem frame and solution in ways that support verification and validation processes [4, 5]. Further, in educational spaces, reflection can be helpful to individuals who are working to develop their professional identities and understand their position and responsibility as engineers in relation to the problems they are tasked with.

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