International Journal of Engineering Education Vol. 35, No. 6(B), pp. 1907–1917, 2019
Printed in Great Britain

0949-149X/91 $3.00+0.00

Decision Making in Engineering Capstone Design: Participants' Reactions to a Workshop about Diverse Types of Reasoning*

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Engineers are expected to make decisions in the context of design, which is ill-structured. Capstone courses serve as an opportunity for engineering students to engage in design and practice making decisions that do not have a single correct answer. Empirical research has demonstrated that when making such decisions, people use informal reasoning, of which there are multiple types: rationalistic, intuitive, and empathic. Despite this reality, engineering education often portrays decision making in the context of engineering design as objective. For example, capstone design instruction typically focuses on providing students with tools to facilitate rational reasoning alone. In this paper, we introduce a framework for informal reasoning that can be used to think critically about how we teach decision making in the context of engineering capstone design. In addition, we use this paper to briefly describe the ways in which capstone design conference attendees engaged with this framework when it was presented in a workshop during the 2018 Capstone Design Conference. To conclude, we present preliminary recommendations for capstone design educators to integrate more opportunities for diverse and realistic forms of reasoning in their teaching practices.

Keywords: design; decision making; capstone; reasoning

1. Introduction

We live in a complex world; many of the problems that engineers contribute to solving cannot be solved by simply applying a formula. Engineers are called to serve as key decision makers in society [1] and design is the major keystone of the engineering profession [2]. Design problems are ill-structured, open-ended, and possess more than a single right answer [3]. As such, engineers must make design decisions in the midst of ambiguity, and their decisions have implications for the well-being of society. The engineering education community is full of large-scale calls to prepare students that can solve design problems with more comprehensive perspectives, such as leveraging creativity [4], engaging in team work across cultures [5], and using global thinking skills [6]. In addition, undergraduate engineering programs are required to develop students' ability to use engineering judgment while also considering global, cultural, social, environmental, and economic factors in the context of engineering design [7]. Therefore, it is important that undergraduate engineering education prepares students to make decisions in contexts that are ill-structured, complex, and do not possess a single right answer.

To prepare engineering students for the realities of engineering work, we have a responsibility to provide them with realistic perspectives of how decision making occurs within the context of engineering design. Engineering students commonly spend the bulk of their time in undergraduate education solving engineering science problems, which are well-structured and converge to a single right answer [2, 8]. For these types of problems, the problem solver has the needed information and an established rule or algorithm of some sort to arrive at the correct answer. Solving these sorts of problems is possible by relying primarily on formal, mathematical, and deductive reasoning. In contrast, decisions made in the context of engineering design often do not possess a single right answer. As such, the decision maker is required to use informal reasoning, which is broader and more inclusive than formal reasoning. Informal reasoning is also needed for decisions that are subject to multiple perspectives and require negotiation [9]. In addition to the cognitive domain used with formal reasoning, informal reasoning includes the affective domain, including empathy and intuition, which contribute to how we make decisions when the outcome is debatable [10]. We are interested in how engineering education can portray decision making in the context of design as including not just formal or rationalistic reasoning, but additional and diverse types of reasoning, such as empathic and intuitive reasoning.

In undergraduate engineering curriculum, capstone design courses are commonly relied upon to expose engineering students to real-world engineering work by engaging them in highly contextualized, ill-structured design projects. Consequently, those

* Accepted 20 May 2019.

who are involved in capstone design are important stakeholders for this work on understanding how to shift undergraduate engineering education to be more realistic with respect to the types of reasoning required for decision making in the context of design. This paper describes our efforts to engage with individuals involved in capstone design via a discussion-based workshop. The discussion topics of the workshop included the different types of informal reasoning we believe are inherent to engineering design and are important to convey to our students. Rather than reporting original research, the contributions of this paper are as follows:

1. Highlight the gap between the ways in which we portray decision making in undergraduate engineering education and the realities of practice
2. Introduce a framework for the types of reasoning required when making decisions in the context of ill-structured problem solving
3. Summarize and interpret the ways in which attendees at our workshop at the 2018 Capstone Design Conference reacted to this framework
4. Make recommendations for engineering educators and convey our plans for future work

We believe this contribution is important because engineering students are often limited in their exposure to decision making approaches that go beyond just rationalistic tools or perspectives, and intuitive and empathic reasoning are often absent from the explicit discourse in engineering education.

2. Background

In this section we address (1) decision making in engineering design, (2) a theoretical framework for informal reasoning, and (3) common practices for teaching decision making in engineering capstone design courses. We use this section to provide some background on these constructs and the way that we have chosen to operationalize them. We also describe the theoretical framework that we presented in the workshop, which we consider as an initial starting point for this line of inquiry around the realities of the need for multiple types of informal reasoning to engage in decision making in the context of engineering design.

2.1 Decision making in the context of engineering design

The functions of engineers in society are extremely broad, and the decisions that engineers make in professional settings possess a significant amount of variation. We are focused on decisions that are made in the context of design, which is the keystone of engineering [2]. Decision making is central to navigating the complex and ill-structured problems that engineers are expected to contribute to solving [11, 12]. Workplace engineering problems are complex because they are ill-structured; they have both engineering and non-engineering constraints and measures of success [13]. Realistically, hundreds of decisions, both implicit and explicit, may be made in just a couple of hours during the design process [14]. To further scope our inquiry, we focus on just explicit 'decision points', where an individual or team explicitly makes a committed choice between a finite number of options. This operationalization of decision making is in alignment with previous definitions of engineering decision making as weighing the alternatives and assigning value to select from a finite number of options [3, 15, 16]. While many decisions are made without an explicit choice between finite options [17], we begin our discussion here as a way to frame the conversation around an accessible operationalization of decision making.

Observational research of engineers in practice has revealed that, while decision makers may justify their design as though it was a result of a strictly logical and rational processes, in reality, the engineers progress through the design process in a complex way, fueled by significant amounts of informal reasoning [18]. This difference has been previously identified as the gap between prescriptive, or normative, approaches to decision making and descriptive, or naturalistic, approaches to decision making [19]. The influential work of behavioral economists has provided robust, empirical evidence that in addition to utilizing rational, slow, and intentional thinking in decision making, our decisions are also guided by more intuitive, automatic, and effortless reasoning [20]. Intuition plays a particularly important role in real-world decisions because they are made in unstable environments [21]. Professional engineers have been observed to check the results of more formal, or rational, evaluations of design options with their own intuition [22]. In addition to the reality that engineers use intuitive reasoning (especially valuable where they have developed expertise), engineers are encouraged to frame their design work as human-centered. Designing for others requires empathic reasoning to understand the user and other persons or systems for which the design decisions have implications [23]. Ultimately, maintaining a connection with humans and their needs is central to all design [24, 25]. Other scholarly work claims that design (more broadly) has experienced a paradigm shift towards a focus on humans rather than on technology, which requires the use of empathic reasoning for design decisions [26].

2.2 Theoretical framework for types of reasoning

As a starting point for this conversation, we draw on the findings of science education researchers, who developed an empirical and emergent framework for the types of informal reasoning that undergraduate students employ when making sociotechnical decisions. Similar to engineering design, sociotechnical decisions are complex, debatable, and have ethical implications. Furthermore, we have selected this framework because it captures what existent work on the reality of engineering decision making demonstrates, namely the use of empathy and intuition to navigate ill-structured design problems. Sadler and Zeidler's [27] framework includes three distinct types of informal reasoning: rationalistic, emotive, and intuitive. First, they define rationalistic reasoning as based on cognitive processes that employ reason and logic; this form of reasoning is often impersonal. For example, an individual may utilize rationalistic reasoning by focusing on the pros and cons of a decision. Second, they define emotive reasoning as similar to rationalistic reasoning in that it is cognitive, but emotive reasoning is distinct from rationalistic reasoning in that it is motivated from a place of care (affective), and considers multiple perspectives. For example, emotive reasoning may also weigh the pros and cons of a decision, but do so based on how someone else may view or be affected by the decision. Third, they define intuitive reasoning as an immediate reaction to a situation; this form of reasoning manifests as an inexplicable gut feeling and often comes from experience.

This framework has been selected as a starting point because it draws on empirical research to understand the realistic ways in which people employ different types of reasoning when making decisions that don't have a single correct answer. We modified the framework slightly by defining the emotive category strictly as involving empathy, and without the distinction of being motivated by emotion. We believe this change is reasonable because the original authors of the framework acknowledge how emotions may be a pervasive influence when students make decisions, especially for decisions with ethical implications [27]. Furthermore, we adhere to the view that emotions are fully integrated into our thinking, and the divide between cognition and emotion is false [28–30]. Another justification for our modification of the original framework is that we are interested in applying this framework to decisions made in the context of engineering design, which may not always spark an emotional reaction, but do consistently require the use of empathy, which Sadler and Zeidler defined as the action of "feelings of concern for other individuals' needs" [27, p. 115]. Therefore, while we did present the framework in the workshop using the term 'emotive,' we described this type of reasoning as coming from a place of care or empathy and not as a cognitive process motivated by emotion. Fig. 1 summarizes the framework as it was introduced to workshop participants.

2.3 Common practice for teaching decision making in engineering education

Despite evidence from extant research that (1) human decision making is never strictly rational, and (2) engineering design decisions require informal reasoning since they don't have a single correct answer, engineering education continues to focus primarily on teaching rational tools for decision making, which is incomplete and unrealistic compared to the way that decisions are made in engineering practice. Engineering programs commonly teach prescriptive decision-making approaches, such as utilizing decision matrices (Pugh method) or following a quality function deployment procedure. Books focused on decision making in engineering convey almost entirely rational methods [31]. Of course, engineering design decisions are required to be evidence-based, and we recognize

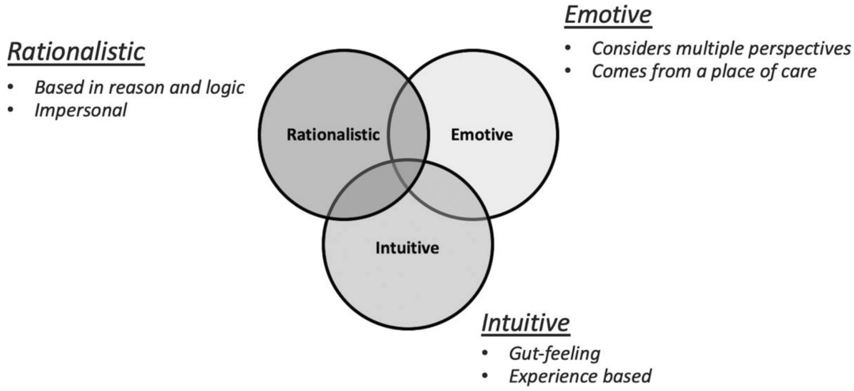

Fig. 1. Theoretical Framework for Types of Reasoning Needed in Engineering Design Decisions.

that rational tools are required and extremely valuable in engineering work. Fluency in solving well-structured problems and in conducting technical analysis are strengths of undergraduate engineering curricula. However, portraying all decision making, including decisions made in the context of design, as a formal and rational activity is not reflective of the ways in which professionals actually work [17, 32].

In engineering education, the focus on rational tools reflects a broader characteristic of engineering culture. Making use of rational reasoning in decision making has been identified as the central theme that unifies engineers regardless of discipline or subdiscipline [33]. Indeed, much of decision making in engineering design is derived from the assumption that humans behave in rational ways; their choices are assumed to be based solely on utility [34]. Addis [35] describes the misconception held by non-engineers that engineering design and decisions result from strictly rational or logical processes as the "rational fallacy." This portrayal of engineering is also evident in ongoing work to integrate engineering into K-12 education. A recent publication recommended introducing decision matrices to middle school students in order to demonstrate how engineers "objectively examine solution options" [36]. Engineering students may subscribe to these dominant narratives in engineering too, as engineering education culture is centered on the assumption that engineering approaches to problem solving are superior to that of other, less scientific, disciplines [37]. Despite this norm in engineering culture, a portrayal of decision making in engineering design as strictly rational is not realistic. While we obviously do not advocate the removal of analytical problem solving and formal reasoning from undergraduate engineering education, we are interested in understanding how we, as engineering educators, can move beyond teaching rational tools for decision making alone. We aspire to understand a way of teaching engineering capstone that helps students develop a more nuanced and realistic approach to decision making that aligns with what we know about engineering design practice and human decision making in general.

3. Decision-making workshop at 2018 Capstone Design Conference

This section provides readers with a summary of what occurred at the decision-making workshop where attendees engaged with two of the authors (Dringenberg and Abell). The overarching goal of the workshop was to engage attendees in reflection and discussion about the importance of developing engineering students as robust decision makers, with a focus on students in engineering capstone design courses. Attendees of the workshop included faculty members, department chairs, laboratory support staff, and both undergraduate and graduate students. The various roles represented by the approximately 30 attendees provided for vibrant discussion and diverse viewpoints.

The facilitators of the workshop presented relevant research on decision making [3, 11] and shared the theoretical framework for informal reasoning (see Fig. 1). It is important to note that the goal of the workshop was not to 'teach' the participants about decision making or teach them how to think about decision making. Rather, the framework and related research was shared in order to provide a lens for the participants to think critically about the types of reasoning that are being supported in their own capstone courses. Specific goals of the workshop were to:

1. Facilitate discussion and reflection about the types of decisions students frequently make in capstone design courses
2. Elicit participants' perspectives on the explicit methods used to teach decision making to capstone students, based on their own experiences
3. Elicit participants' perspectives on the ways in which engineering design decisions are typically made in practice
4. Facilitate discussion and reflection on the differences between the ways that capstone students and practicing engineers make decisions
5. Discuss and synthesize approaches that could integrate more realistic types of reasoning (beyond rationalistic) for decision making into capstone design instruction

The facilitators started the participatory aspect of the workshop by having attendees collectively brainstorm a list of decisions that engineering students might typically make during their capstone courses. The ultimate list encompassed a wide array of results, which is shown in its entirety below (some responses have been edited for clarity, and redundant responses have not been included):

- How much time to allow for each phase of a year-long project
- Appropriate materials to build a prototype
- Which team members will perform which tasks
- How the prototype will be tested
- When/if it's time to change direction (design pivot)
- How to weigh priorities
- Budget size/allocation
- Down-select alternative concepts
- Methods of manufacturing/construction
- Balancing form vs. function

- When to make a custom part vs. buy one off the shelf
- How/when to identify risks, for both assessment and mitigation plans
- When to abandon an idea or concept
- When/if to rework or redesign a concept
- How to help the client scope a project
- How to understand the client's real goals
- How to select a final concept
- How to understand when it's time to stop designing
- How to assign roles to team members
- How to construct a certain part of the design
- How to find end users to interview
- How to determine which goals are the highest priority on the project
- How to deal with conflicting viewpoints from faculty members and industry sponsors

Upon reviewing the list, the facilitators chose one of the decisions from the list to use as an example to frame subsequent activities, discussion, and reflection with all workshop attendees. The chosen decision was "when/if it's time to change direction", and rephrased to the workshop participants as "*How do I know when it's time to change direction in a project?*" The facilitators chose this decision from the full list because it was likely a question that would come up for all students in capstone courses, regardless of the major, discipline, or style of capstone project, so it would likely be relatable to all participants in the room. Additionally, this decision was chosen because there isn't a single right answer to this question, and the decision is debatable. Therefore, the person making the decision would likely use some combination of the three types of informal reasoning to reach a conclusion. After this selection, the facilitators directed an activity to initiate small-group discussion and reflection on a series of questions that were posed to workshop attendees:

1. Which type(s) of reasoning would practicing engineers or designers use to make this decision?
2. Which type(s) of reasoning would capstone students use to make this decision?
3. Which type(s) of reasoning are explicitly taught to capstone students?

The facilitators posed the questions sequentially so discussion groups could focus on one scenario at a time. The participants self-selected into 13 discussion groups of roughly 2–5 people per group. In order to record some of the results of the discussions, a large poster containing the framework for types of informal reasoning (Similar to Fig. 1) was placed on the wall at the front of the room. After each round of discussion, every group sent a representative up to the poster to place a sticky note on the framework to indicate the type(s) of reasoning their group thought would be used in that given scenario. The next three subsections summarize the results of this activity. The facilitators took photographs of the framework poster as the workshop progressed, to document the changes as additional scenarios were discussed. For clarity, the photographs of the framework were reformatted as black & white illustrations for this publication.

3.1 Which type(s) of reasoning would practicing engineers or designers use to make this decision?

To indicate their responses to the first question, each participant group placed a sticky note on the framework poster, represented by a black hexagon in the figures. As seen in Fig. 2, the majority of the participants believed that practicing engineers would use a combination of rational and intuitive reasoning to decide when it might be time to change direction on a project. One group thought the practicing engineers would instead incorporate some combination of intuitive and emotive (empathic) reasoning, while two groups thought the engineers would use entirely rationalistic reasoning. One or two final groups thought the engineers would use a combination of all three types of informal reasoning.

3.2 Which type(s) of reasoning would capstone students use to make this decision?

To indicate their responses to the second question, participant groups each placed different sticky note on the framework poster, represented by a gray square in the figures, overlaying the existing responses from the previous question. The responses to this question show that participants perceived that emotive (empathic) reasoning would factor more into the same decision made by the capstone students, as compared to the practicing engineers. There were several groups that placed their sticky notes in the very center of the diagram, indicating that they thought the students would use a combination of all types of reasoning. One group conveyed their belief that students would use a combination of rationalistic and emotive (empathic) reasoning. Additionally, there were two groups that placed their sticky note solely in the rationalistic zone, indicating that they thought capstone students would make the decision using only that approach.

3.3 Which forms of reasoning are explicitly taught to capstone students?

To indicate their responses to this third question, the participant groups placed yet another round of

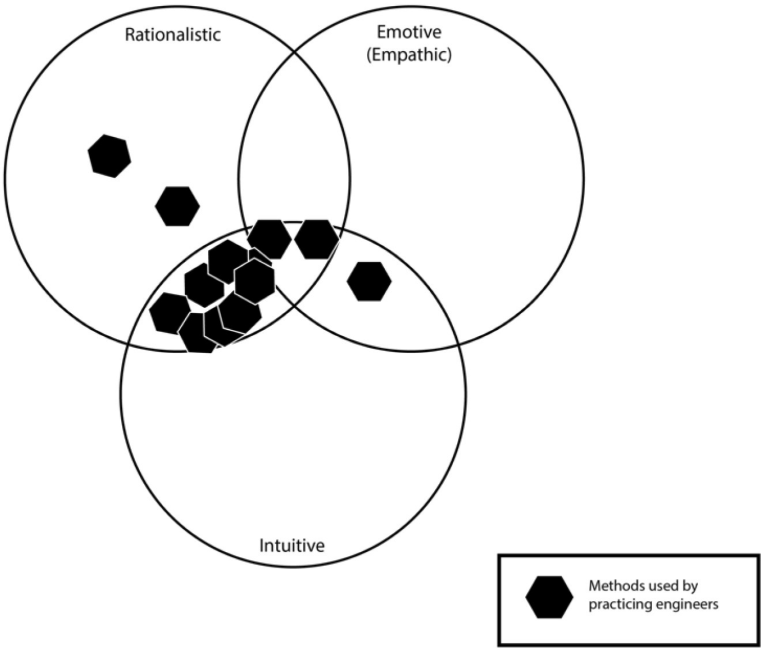

Fig. 2. Workshop Participants' Responses to How Practicing Engineers or Designers Would Make the Decision.

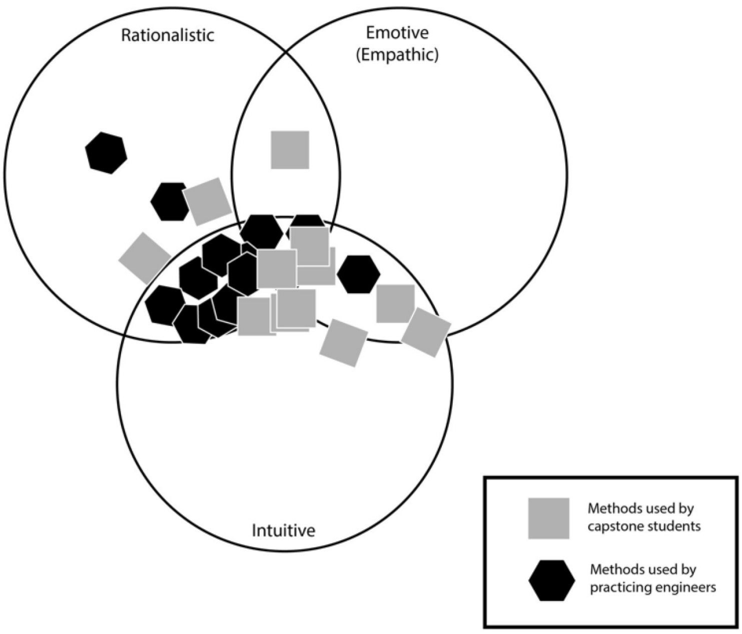

Fig. 3. Workshop Participants' Responses to How Engineering Capstone Students Would Make the Decision.

sticky notes on the framework poster, represented by light gray circles in the figure, to somewhat more scattered results than the first two rounds, as shown in Fig. 4. Four groups conveyed a belief that only rationalistic reasoning is taught, while the same number expressed that both rationalistic and empathic reasoning is taught. At least two groups indicated that all three types of reasoning are taught, while a single group placed their sticky note at the intersection of rationalistic and intuitive reasoning. This question prompted a lively discussion, with participants asserting many different views based on their own experiences. The mix of faculty members, students, administrators, and staff members in the room allowed for an exchange of ideas and viewpoints. One interesting result from this round of discussion is that, while placing their final sticky note during this round, two participants took it upon themselves to use a marker to modify the framework to include two extra zones in the

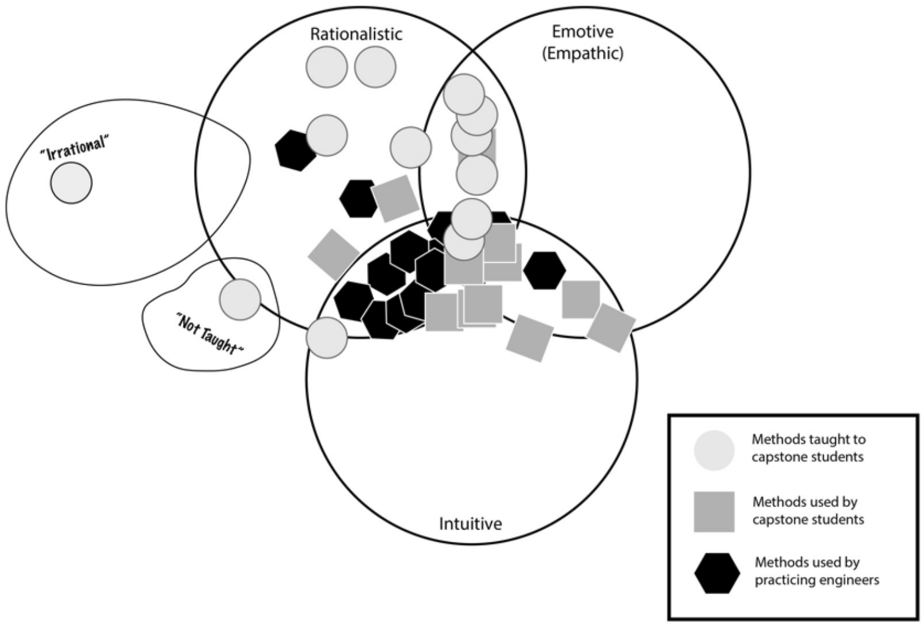

Fig. 4. Workshop Participants' Responses to What is Explicitly Taught in Capstone Design Courses.

diagram: "*irrational*" and "*not taught*." Given the time constraints of the workshop, the facilitators did not have time to follow up on these participant-generated additions to the diagram, however it is strongly suspected that the category of "irrational" was added in a light-hearted manner—perhaps as an acknowledgement of their view of students as novice decision makers.

4. Reactions of workshop participants

To conclude the workshop, the facilitators held a guided discussion to synthesize the workshop participants' reactions surrounding the results of the sticky note activity. First, participants were asked to take a minute to silently reflect on their reaction to the visual results of the completed framework poster. Then participants were prompted to each come up with a one-sentence statement to summarize their reaction to the results. Participants who felt comfortable to do so shared their results with the room, and the facilitators took notes on their statements, capturing them in real time. Not all statements were complete sentences. The following statements were shared by participants, edited only for grammatical clarity:

- Teach the union of rationalistic, intuitive, and empathic.
- The [reasoning used by practicing engineers] is the union of the [reasoning used by capstone students] and the [forms of reasoning taught to capstone students].
- Instruction may push students to add greater rationalistic approaches to mirror the instructor's approaches.
- We try to teach rational thinking because we think that's what industry wants, but we may need more balanced approaches.
- Students have limited experience and often fall back on emotional approaches.
- Neither practitioners nor students do what we [instructors] think is right.
- We don't teach what's used by practicing engineers, so students use a variety of approaches.
- Academia is attempting to change industry practice by teaching students to think more customer-centric.
- Integrate rational, emotional, and intuitive.
- The forms of robust reasoning taught to students differ from the ways practicing engineers make decisions.

This range of responses led the workshop into a lively discussion that solicited input from participants on ways that capstone design educators could support diverse forms of reasoning in decision making. Generally, the participants recognized and agreed that there was a discrepancy between the reasoning types employed by practicing engineers versus those employed by capstone students. However, the participants exhibited a wide spectrum of opinions on what the *cause* of this discrepancy was, or even if the discrepancy was a problem worth tackling in the context of undergraduate education. We summarize a few highlights below.

4.1 *Resistance to teaching types of reasoning other than rationalistic*

One attendee framed their view in terms of thinking about customer-centered design. The participant supposed that industry is actually the 'customer base' of capstone design, in that one goal of capstone courses is to prepare students for the workforce. From this viewpoint, the participant argued that there is no need for capstone courses to teach multiple forms of reasoning because the customer (industry) is not asking for workers with skills beyond rationalistic reasoning. The participant recognized the discrepancy in the types of reasoning used by practicing engineers and capstone students; however, they stood firm in their view that it was not the job of capstone educators to close this gap.

A second participant acknowledged that the results of the activity showed a discrepancy in types of reasoning used by capstone students versus types used by practicing engineers. However, this participant suggested that capstone educators may not want to make a change to explicitly teach intuition. The participant took the view that intuition is based on tacit knowledge, and one only gains tacit knowledge (and thus intuition) from extended practice and experience. The participant further explained that they believe that teaching only rationalistic decision making was sufficient, because rationalistic methods are a critical part of making engineering decisions, and that the students would, in time, develop intuition based on their own experiences and practices in engineering industry.

4.2 *Enthusiasm for teaching types of reasoning other than rationalistic*

In contrast to the ideas expressed above, many participants found value in the idea of giving capstone students guidance on and experience in all three types of reasoning used for decision making in the context of engineering design. One participant presented the view that it would be useful to explicitly teach students all three methods of reasoning because capstone educators do not know where their students will end up, professionally speaking. This participant supposed that practicing engineers in different fields likely use different combinations of reasoning in their work. For example, an engineer doing a detailed design of an aircraft engine may use very different types or amounts of reasoning to make decisions as compared to engineers who design consumer-facing products, such as refrigerators or smart phones.

Also, in support of teaching multiple types of reasoning, several other participants supported the idea that capstone educators should give students ample opportunities to brainstorm and generate multiple ideas, which would allow the students to practice intuitive and emotive (empathic) reasoning and then, have the students use rational reasoning to down select and evaluate ideas.

Despite the participants' divergent views in some areas, the overall tone in the discussion was that reasoning for decision making is indeed an important part of engineering and capstone education, and that the two were inherently linked. One participant even went so far as to say that 'design is the evolution of information punctuated by decisions.'

5. Discussion of participant reactions

In general, we were encouraged by the ways in which workshop participants engaged with this framework for informal reasoning as a lens to consider our efforts to develop students as engineers in capstone design courses. Participants used the framework as a way to examine the misalignment between the ways in which decision making is portrayed in engineering education, and the more complex reality of the ways in which engineers actually make design decisions in practice. Reactions that we should adjust our teaching approaches to close this gap echo many other calls to do so in engineering education, such as the call for engineers to have more professional skills [38], develop global competency [5, 39], and pursue lifelong learning [40, 41]. This call to adjust teaching approaches to include more forms of reasoning can be difficult to act on, given the ever-present pressure to add more and more competencies to the undergraduate curriculum. While we do feel that there are ways to integrate diverse forms of reasoning into engineering education, we recognize that earning a Bachelor's degree is just the beginning—engineers build decision-making skills as they gain more real-world experiences. Additionally, we appreciate the tension that was articulated between academic or theoretical ways that decisions should be made and the reality that some decisions in industry are made as business cases, which may discourage the use of empathy. We agree that certain types of reasoning may be more appropriate in certain phases of the design process. For example, we recognize that intuitive reasoning may play a larger role toward the beginning and end of the design process, and may play a much smaller role when making detailed design decisions or selecting concepts [42]. We also appreciate the point that undergraduate engineering students lack experience in design, so we as educators should align our expectations with their skills and experience levels; likely, undergraduate students will not be able to consistently leverage meaningful intuition to guide their design decisions.

In the context of engineering design decisions, we believe that further consideration of this framework should distinguish between shallow intuition (uninformed guesses) and deep intuition (expertise). One final discussion point is that during the conference workshop we learned that the word 'emotive,' even when defined as the use of empathy, may inhibit the communication surrounding this framework for types of reasoning. The word 'emotive' triggers the idea of emotions, which may be perceived by some as an enemy of engineering reason, and as a result, the use of the word may distract people from the fact that emotive reasoning ultimately involves considering a decision from the perspective of someone else, such as an end user.

6. Recommendations for capstone educators

In general, we recommend that capstone educators (or other engineering education professionals) utilize the framework and ideas presented in this paper to reflect on their own approaches to teaching engineering decision making in the context of design. We perceived that the majority of attendees at our workshop found the exercise useful, even if only to explicitly highlight potential gaps between the portrayal of decision making in undergraduate engineering school and reality of decision making in engineering practice. Because this was not a research study, we do not have findings that can directly inform recommendations for our community. Instead, we offer some ideas for potential opportunities to integrate diverse types of reasoning into capstone design in engineering.

We believe that user-centered or human-centered design is already widely prevalent in capstone design, and this serves as an opportunity to talk about the importance of considering design decisions from multiple perspectives, or utilizing empathic reasoning, with students. Previous work by the first author has demonstrated that even some first-year engineering students are able to utilize multiple perspectives in their experiences with ill-structured problems, both within and outside of their design team, [43]. As a result, we believe that capstone design educators can convey the importance of empathic reasoning by way of encouraging students to consider multiple perspectives during the design process. Educators can facilitate this practice by having students interact with end users, clients, or other stakeholders relevant to the project at hand. By directly interacting with the stakeholders, students can gain insight into the perspectives of people in different situations, which the students can incorporate into their decision-making process for certain aspects of the design project.

With respect to intuition, we point to salient opportunities as we have in our previous work on intuition: first and foremost, instructors should introduce the concept of intuition to their students and explain that intuition is commonly experienced as an emotion or feeling that often comes with the development of expertise in a given field. In a capstone design setting, instructors can have students practice accessing their intuition by having students do an initial 'guess' on how well a solution will work, or having them do a 'gut check' on a final solution that the team has chosen [42]. Additionally, instructors can facilitate student engagement with industry partners or practicing engineers from the community. This engagement could be somewhat formal and take the form of a year-long mentorship of capstone teams, or it may happen more informally by way of inviting practicing engineers to attend student presentations. This engagement can allow the students to access to these practicing engineers' more powerful intuitive reasoning, based on their years of experience and expertise. Although these changes seem subtle, we believe they may help shift towards a more realistic portrayal of engineering decision making. Furthermore, we believe that many of these practices take place already, and that it may support students developing more realistic ideas about engineering decision making by just speaking explicitly about the role of the different types of reasoning. We also recognize that such recommendations may be met with resistance as they are up against the prevailing theme of engineering culture, which is one of objectivity and logic.

7. Conclusion

Engineers are required to make design decisions, and because these decisions do not possess a single right answer, they require the use of multiple types of reasoning. Despite substantial evidence that humans use intuitive and empathic reasoning to guide their decisions in ill-structured environments, engineering education predominantly teaches strictly rational approaches to decision making. In order to invite a conversation about this gap between realistic decision making and common practices for teaching decision making in capstone engineering courses, two of the authors facilitated a workshop where they presented a theoretical framework for informal reasoning. This framework includes three distinct types of reasoning: rationalistic, intuitive, and emotive (empathic). When this framework was presented in a workshop at the 2018 Capstone Design Conference, attendees reacted in divergent ways—a few were resistant to the idea of teaching more diverse forms of reasoning, and many agreed that there is a need to do so. Many attendees were intrigued by the discussion and agreed that there was a misalignment between the reality of engineering decision making and the way it is portrayed to students in capstone. We received feedback that we are in the path of addressing a need in capstone design practice at the undergraduate level with our work on the use of informal reasoning in engineering design. Based on this experience and our prior work, we provided some concrete recommendations for capstone educators to utilize practices that are already in place, such as user-centered design and industry partnerships, as ways to highlight the role of empathic and intuitive reasoning along with rationalistic reasoning for decision making in engineering design.

8. Future work

We are currently conducting formal research to explore and characterize the beliefs that both capstone faculty and capstone students hold about the role of different types of reasoning used by engineers to make design decisions. This investigation will also provide insight on how the formal decision-making instruction provided in capstone design influences students' beliefs about the types of reasoning, as we are collecting data from capstone students at both the beginning and the end of year-long capstone design experiences. Additionally, we are currently modifying the framework for reasoning presented in this paper based on the data we have collected so far from capstone students. We believe this work will be a contribution for others interested in studying students' beliefs or behaviors when it comes to decision making in ill-structured settings. To continue the discussion we have aimed to start here, we invite engineering educators who are interested in providing insights on how they teach decision making to engage with us. We are excited to continue to pursue our vision for a future where decision making in engineering education is more realistic and inclusive with respect to diverse types of reasoning.

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