Structural Engineering Heuristics in an Engineering Workplace and Academic Environments

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Abstract: Heuristics are approaches engineers use for solving problems and making decisions with quick, often approximate, calculations and/or judgement calls. Such approaches have become marginalized in structural engineering education to make room for more theoretical and precise approaches. As a result, engineering students are less confident with heuristics and firms believe students are unprepared for using such approaches to solve messy real-world problems. This research identified and described heuristics within the social and material contexts of a structural engineering workplace and undergraduate structural engineering courses to better understand the use of heuristics in these environments. The researchers used ethnographic methods to access these environments and document the social and material contexts wherein heuristics are applied. Two different types of heuristics were found: practice-based heuristics, and profession-based heuristics. Practice-based heuristics are more dependent on an individual's or organization's experience with certain projects. Profession-based heuristics are grounded in a discipline's fundamental concepts, and therefore are less context-dependent. **DOI: 10.1061/(ASCE)EI.2643-9115.0000029.**

Introduction

Heuristics frequently are defined as rules of thumb that are used to derive quick and/or approximate solutions (Gestson et al. 2019; Ruddy and Ioannides 2004; Schoenfeld 1992). Within the profession of structural engineering, designers have developed heuristics over time to solve recurring structural design problems with simple and expedient approaches that were appropriately accurate for their purposes (Ruddy and Ioannides 2004). The development and application of such heuristics requires engineering judgment and understanding of the concepts that matter most when solving a particular problem (MacRobert 2018; Ruddy and Ioannides 2004). Thus, heuristics are a way for structural engineers to selectively and readily represent concepts relevant to solving a problem at hand (MacRobert 2018; Tversky and Kahneman, 1974), such as having an intuitive sense of the magnitude of loads and the demand they induce on structures to quickly select a preliminary sized member during schematic design (Ruddy and Ioannides 2004).

Over the last half century, however, structural engineering education gradually has shifted its focus toward more theoretical representations and understanding of fundamental concepts, and away from the pragmatic, heuristic representations necessary for solving real-world messy problems (Aparicio and Ruiz-Teran 2007). This shift has been perceived as contributing to recent engineering graduates lacking the engineering judgment to creatively apply and develop heuristics for solving these messy problems they will encounter in the workplace (Aparicio and Ruiz-Teran 2007; Bernold 2005; MacRobert 2018). Gaining a deeper understanding of how heuristics are developed and applied in engineering therefore could provide a potential bridge between the theoretical focus of engineering education and the engineering judgment demanded in practice. However, this potential bridge between engineering education and practice that heuristics offer has received limited exploration in engineering education research.

One of the challenges to teaching heuristics in engineering education is comprehending and appreciating the social and material (sociomaterial) contexts wherein heuristics are formed, taught, and applied in academic and workplace environments. These contexts can influence considerably the degree to which a heuristic is applicable to other environments (Johri and Olds 2011; Tversky and Kahneman 1974). Social contexts are the people intrinsic to the formulation, teaching, and/or application of knowledge. Material contexts are tools intrinsic to the formulation, teaching, and/or use of knowledge (Johri and Olds 2011). Learning theories that emphasize the role of environment in learning have recognized how these contexts influence the transfer of knowledge, including heuristics, to other environments (Newstetter and Svinicki 2014). For example, teaching students a heuristic solely for solving a single-solution textbook problem may limit the opportunity for students to understand how and when such a heuristic could be useful in solving messier, although similar, problems in practice. Thus, identifying and describing heuristics within the contexts in which they are applied is worthwhile to the engineering education community because—although heuristics are relevant to engineering practice (Koen 1984)—some heuristics may be more-or-less universal across contexts and, therefore, require a more nuanced approach when taught in the classroom.

The study presented herein is the first to explore the use of heuristics in both academic and workplace settings, specifically pertaining to structural engineering. The purpose of this research was to identify and describe heuristics within the social and material

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contexts of a structural engineering workplace and undergraduate structural engineering courses to better understand how heuristics are developed and applied across these environments. Defining and characterizing heuristics in such a way provides a future avenue for further understanding of engineering practice because the development and use of heuristics within certain contexts provides access into practicing engineers' ways of thinking and problem solving. Deeper understanding of heuristics in this manner potentially could help to bridge the gap between education and practice because it allows for heuristics to be the vehicle that engages students into thinking like practicing engineers, rather than heuristics being perceived as universal approaches for solving certain types of problems.

Background

Heuristics in Structural Engineering Education and Practice

Heuristics are quick, often approximate, intuitive approaches to solving problems and making decisions when conditions surrounding the problem or decision are uncertain (Gestson et al. 2019; Schoenfeld 1992; Tversky and Kahneman 1974). For example, Daly et al. (2012) studied product designers in the early design process and found 77 different design heuristics in these processes. This work highlights the role of heuristics in initial idea development and how they are used as cognitive shortcuts in engineering design. A related study by Lee et al. (2018) examined the use of design heuristics in concept generation and noted that the use of heuristics was prevalent in the ideation phase and continued through the design phase. More simply put, the entire engineering method has been described as the use of engineering heuristics (Koen 1984). Deckert (2018) proposed using heuristics to develop creativity in engineering students and developed a framework for doing so, but there has been limited work on heuristics in engineering education to date.

Before the advent of computers, heuristics were a useful resource for structural engineers designing indeterminate structures and for handling frequently reoccurring structural design problems (Aparicio and Ruiz-Teran 2007; Ruddy and Ioannides 2004). As computational tools became more prevalent in the profession and allowed for more theoretically precise calculations over the last half century, some historically established heuristics were demonstrated to be wrong or evolved into quick checks of software output (Aparicio and Ruiz-Teran 2007). At least partially as a result of this, structural engineering education progressively focused more on theoretical knowledge and less on the pragmatic, intuitive knowledge and engineering judgment demonstrated through heuristics (Aparicio and Ruiz-Teran 2007; SEI 2013). A justification for this transition and continued focus in structural engineering education was that if structural engineering students received sufficient training in the fundamental concepts of mathematics, physics, and mechanics, they would be prepared to apply those concepts in structural engineering practice (Aparicio and Ruiz-Teran 2007; Balogh and Criswell 2013; Robertson 2002). However, this type of education also has led to the belief that engineering students struggle to apply theory to real-world problems that require less precise, albeit acceptable, solutions (Aparicio and Ruiz-Teran 2007; Bernold 2005; Jonassen et al. 2006; MacRobert 2018; Wirth et al. 2017).

This lack of preparedness partially can be explained by situated cognition theory, which posits that conceptual knowledge to some extent is limited to the social and material contexts wherein said knowledge is learned and applied (Johri and Olds 2011). Thus, students may struggle to apply theory to the real world when the sociomaterial contexts wherein theory is taught differs considerably from the sociomaterial contexts of how theory is applied in practice.

Situated Cognition and Heuristics as Conceptual Representations

Situated cognition is a learning theory that emphasizes learning as being inextricably linked to doing (Greeno et al. 1996). Situated cognition, unlike other learning theories, places a greater emphasis on the role of social and material (sociomaterial) contexts wherein learning and knowledge application occurs, rather than limiting it to the mind of the individual learner (Johri and Olds 2011; Newstetter and Svinicki 2014). Sociomaterial contexts are the people and tools utilized when learning through doing occurs. Within engineering and engineering education, people relevant to learning are other engineers, peers, teachers, mentors, and project stakeholders, for example. Some common examples of tools are design manuals, drawings, software, textbooks, and codebooks. When it comes to learning and applying engineering concepts, the sociomaterial contexts wherein said concepts are applied influence how concepts are represented (Lemke 1997; McCracken and Newstetter 2001). For example, Bornasal et al. (2018) observed how practicing transportation engineers represented their understanding of the concept of sight distance through their discussion of project contraints with other engineers and project stakeholders (social context) and through the use of software and design references (material context) on a roundabout project. Therefore, conceptual representations are the sociomaterial contexts that mediate the learning and application of concepts. Some common examples of conceptual representations are language, text, diagrams, symbols, and equations (Lemke 1997; McCracken and Newstetter 2001).

Heuristics also can be considered to be conceptual representations because they are a method engineers use to solve problems wherein certain concepts may be simplified and/or given priority over other concepts that are less relevant to or confounding the problem. For example, a structural engineer may opt to qualitatively sketch the deflected shape of a structure based on their determination of the load path to check software output, rather than performing a complicated hand computation to check the same output. The use of heuristics often is based on experience-based judgments to determine the applicability of certain concepts to a problem, and this makes them highly dependent on the sociomaterial contexts wherein they are applied and the experiences through which that judgment initially was honed (Tversky and Kahneman 1974). Research methods, such as surveys, interviews, and/or focus groups, typically occur when participants are not actively engaged in their everyday engineering work, and therefore limit the opportunity for both researchers and participants to recognize what, how, and when heuristics are being used in particular sociomaterial contexts. One methodology particularly well suited for gaining a deeper understanding of how these sociomaterial contexts influence the conceptual representations of heuristics is ethnography.

Ethnographic Studies of Engineering Workplace and Academic Environments

Ethnography emerged as a methodology from the field of anthropology to access and gain a deeper understanding of cultures by immersing oneself in said culture's environment (Case and Light 2011). Ethnographies of the engineering workplace environment appear to support situated cognition literature in that development of knowledge is highly dependent on social interactions and shared understanding of the tools within their field (Bucciarelli 1988; Trevelyan 2007, 2010). Ethnography has been demonstrated to provide considerable access into the sociomaterial contexts of engineering environments, but has yet to focus this access toward gaining a deeper understanding of conceptual representations, particularly the use of heuristics in engineering practice. Furthermore, very few ethnographies have explored both workplace and academic environments for a specific engineering discipline to understand how heuristics differ across these environments based on their sociomaterial contexts (Johri 2014; Johri et al. 2014). There have been ethnographic studies of engineering education in academic (Godfrey and Parker 2010) and workplace engineering environments (Gainsburg et al. 2010), but not of both environments within a single study.

One ethnographic study of an academic engineering environment occurred at a university in New Zealand, wherein the researchers sought to provide a holistic description of the culture in the university's school of engineering through interviews with and observations of faculty and students in all 4 years of undergraduate study (Godfrey and Parker 2010). Although this ethnography did not specifically examine the influence of sociomaterial contexts on heuristics, Godfrey and Parker (2010) did note that the school's culture emphasized an "engineer way of thinking" that focused on solving problems with best answers over right answers. Similarly, heuristics are strategies used to find appropriate and/or alternative (best) answers suitable for the problem at hand rather than focusing considerable time and effort on an explicitly right answer (Daly et al. 2012; Gestson et al. 2019; Schoenfeld 1992; Warren-Myers and Heywood 2010). Godfrey and Parker's (2010) ethnography focused on engineering education at the New Zealand school in a broad sense and did not examine any specific engineering discipline.

An example of an ethnography of the workplace environment that did focus on a specific discipline is Gainsburg et al.'s (2010) study wherein they observed 19 structural engineers in 3 different workplace environments. Gainsburg et al. (2010) observed these 19 engineers using rules of thumb and estimates which consisted of rough, ballpark calculations and shortcuts used in the schematic design phase that allowed them to move forward with their design with appropriate but less precise values. Rules of thumb and estimates are examples of heuristics (Gestson et al. 2019) and Gainsburg et al. (2010) noted these heuristics as one of the types of structural engineering knowledge that is important in the workplace environment. Although the Gainsburg et al. (2010) ethnography is a valuable study for understanding the types of knowledge used in the structural engineering workplace, it offers little insight into how such rules of thumbs and estimates are generated within the sociomaterial contexts of workplace settings and their relation to academic environments.

Gainsburg et al. (2010) and Godfrey and Parker (2010) only observed the environments they were studying, and did not participate in them. Participation in an ethnography provides the researchers with an additional access point to the sociomaterial contexts of the environment being studied, which can confirm or refute findings made through observations alone (Emerson et al. 2011; Walther et al. 2013). Furthermore, the use of heuristics sometimes can be unobservable to an outsider or not made explicit within the contexts in which it is being used. Participation in the environments being studied allows the researcher to come in direct contact with heuristics and the sociomaterial contexts wherein they are applied to gain deeper understanding of a heuristic's uniqueness or universality.

Methods

An ethnographic approach consisting of participation and observations was implemented to identify and describe heuristics within the social and material contexts of a structural engineering workplace and undergraduate structural engineering courses. To gain access to these contexts, the lead author, hereafter referred to as the ethnographer, worked as a part-time intern at a medium-sized private architecture and engineering firm, and subsequently enrolled in four undergraduate structural engineering courses over two 10-week terms. This staging was based on the timing of when the internship was made available to the ethnographer and the academic terms during which the engineering courses were offered. The ethnographer's own undergraduate and graduate studies have focused on structural engineering, providing him with the basic structural engineering knowledge and jargon to participate in both environments. The firm and the courses selected were based on the firm's willingness to employ the ethnographer as a part-time intern and the instructors' willingness to let the ethnographer enroll in their courses. Both environments were located in Oregon to be geographically accessible to the ethnographer.

While at the firm, the ethnographer performed typical work tasks that would be given to an engineer in training (EIT) for ∼16 h/week and conducted research for the remaining ∼24 h of the work week. The ethnographer did this for 3 months and participated in structural engineering activities on 18 different projects. Table 1 provides additional demographic information about the structural engineers with whom the ethnographer interacted at the firm. For the academic environments, the ethnographer participated in each class as an actual student, attending lectures and recitations, completing homework assignments, and taking exams. Table 2 provides additional demographic information about the instructors and their respective courses.

Data Collection

Ethnographic methods rely on three data collections sources: field notes of participant observations, interviewing, and artifact collection (Johri 2014; Emerson et al. 2011). Field notes initially were handwritten jottings that the ethnographer documented during and after participating in or observing the use of conceptual representations. These jottings were converted into completed typed field notes as soon as possible so that the ethnographer did not forget the information documented in the jottings (Emerson et al. 2011). In the workplace environment, the jottings and subsequent fieldnotes revolved around engineering tasks the ethnographer was assigned as an EIT or their observations of an engineer or engineers

Table 1. Demographic information for structural engineers in workplace environment

Parameter	Value
Number of structural engineers	20[a]
Industry experience in years	0–46 ($\mu = 10.3$)
Number of licensed PEs (SEs)	12 (5)
Number of female (male) engineers	7 (13)
Number of M.S./M.Eng. degree holders	7

Source: Adapted from M. Barner and S. Brown. Forthcoming. "Design codes in structural engineering practice and education." *J. Civ. Eng. Educ.* https://doi.org/10.1061/(ASCE)EI.2643-9115.0000026.

Note: PE = professional engineer; and SE = structural engineer.

[a]The firm employs 24 structural engineers across three offices; however, only 20 were observed in-depth at the office in which the ethnographer participated.

Table 2. Demographic info for structural engineering courses studied

Course	Number of students	Lecture (recitation) (h/week)[a]	Course objective	Instructor teaching (industry) experience (years)[b]	Female or male instructor
Structural Analysis I	60	3 (2)	Determinate analysis	30 (12)	Male
Structural Analysis II	50	3 (2)	Indeterminate analysis	36 (29)	Male
Steel design	67	3 (2)	Beam, column, and brace design	1 (2)	Female
Reinforced concrete design	60	4 (0)	Beam design	22 (24)	Male

Source: Adapted from M. Barner and S. Brown. Forthcoming. "Design codes in structural engineering practice and education." *J. Civ. Eng. Educ.* https://doi.org/10.1061/(ASCE)EI.2643-9115.0000026.
[a]All courses were on a quarter system, meeting 4–5 h per week for 10 weeks.
[b]Some instructors' industry and teaching experience overlap at various stages in their careers.

working on and discussing their design-related tasks. In the academic environments, the jottings were integrated into the ethnographer's lecture/recitation notes and immediately revisited after exiting the classroom and converted into typed field notes. Converting the jottings into typed field notes allowed the ethnographer to identify shortcomings and missed information in the jottings that could be resolved through subsequent interview questions with the instructors and practicing engineers (Emerson et al. 2011).

Formal and informal interviews were conducted with all the instructors and practicing engineers. When possible, formal interviews were preferred so that the ethnographer could record and transcribe the interviews for further analysis. Informal interviews occurred more spontaneously during office hours; following lectures, recitations, and design meetings; or after completing an assignment as an intern. Data collected from both formal and informal interviews were reintegrated into the field notes to shore up missing information or revise misinterpretations from observations (Walther et al. 2013). Artifacts also were brought to interviews and integrated into field notes to provide additional information about the sociomaterial contexts in each environment.

Artifacts were physical objects in the field that were relevant to the context of the ethnographer's participation and observations. Artifacts most commonly took the form of diagrams and text that either were created by the ethnographer and/or participants, or already existed in a material resource, such as a textbook or design aid. Artifacts were collected with pictures following participant consent and then copied and pasted into the pertinent section of the field notes to create an annotated account of the ethnographer's participation and observations. Although the artifacts are the primary material context documented in the field, the artifacts do not exist outside of the social context of their creation and application, and therefore must be integrated into the field notes and supplemented with interview data to fully describe the sociomaterial contexts of each environment. Collectively, these three sources of data collection (field notes, interviews, and artifact collection) allowed the ethnographer to triangulate the data to confirm or refute data collected from any one source (Walther et al. 2013).

Data Analysis

Data analysis occurs simultaneously with data collection in an ethnography due to the interconnectedness of the data sources and to prevent the ethnographer from becoming overwhelmed by the amount of data collected (Emerson et al. 2011; Johri and Olds 2011; Walther et al. 2013). The interconnectedness of the data sources requires the ethnographer to constantly synthesize the data collected from each source to create their annotated accounts of how concepts are represented in each environment. The very act of creating these accounts initiates the analysis process by forcing the ethnographer to triangulate the data and begin identifying common themes within and across each environment that can guide further inquiry to challenge or refute the emergent themes (Emerson et al. 2011; Walther et al. 2013).

Interview transcripts from recorded interviews were iteratively coded with the initial iterations deductively seeking participants' explicit mentions of conceptual representations pertaining to specific accounts in the field notes. Coding is the iterative process of constructing categories that describe common excerpts of text relevant to answering the research question (Auerbach and Silverstein 2003). Subsequent coding iterations were inductive as more transcript data from a variety of participants and contexts became available to begin identifying similarities and differences in conceptual representations across environments (Miles et al. 2014).

Transferability and Credibility

In qualitative interpretive research, it is important to provide readers with sufficient detail so that they can assess the transferability and credibility of the methods and findings (Lincoln and Guba 1985; Walther et al. 2013). With regard to transferability, the researchers acknowledge that the environments studied are not representative of all structural engineering firms or courses. However, the firm studied provides design services for a variety of buildings in the public, industrial, and commercial sectors and employs a diverse team of structural engineers (Table 1). The courses studied, although somewhat dependent on the instructors' curricula and teaching styles, are four of the most common courses in undergraduate structural engineering education (Perkins 2016) and have learning outcomes and curricular materials in common with similar courses across the United States (Kelly 2008; Perkins 2016; Rumsey et al. 2010; Solnosky et al. 2017).

To enhance the credibility of the study, the ethnographer spent 9 months in the field across both environments to expose themself to multiple sociomaterial contexts via participation and observation. Spending several months embedded in multiple environments as a participant and observer allows for more data to emerge that can confirm or refute initial interpretations of the data collected (Case and Light 2011; Johri and Olds 2011). The authors acknowledge that the sequencing of data collection beginning in the workplace and finishing in the classroom creates potential bias in data collection and analysis. To mitigate this bias, the ethnographer focused their data collection on identifying and describing heuristics as they emerged within their own unique contexts, rather than deductively searching for preconceived heuristics in either environment. This allowed for initial interpretations of the data and descriptions of heuristics within any one environment or specific context to constantly be challenged with alternative interpretations from the sociomaterial contexts of different courses, different projects encountered in the workplace, and different instructors and practicing engineers being interviewed. Participation in both environments also was critical to identifying and documenting heuristics within their sociomaterial contexts, because observation alone

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would not have provided the ethnographer with explicit heuristic applications in the workplace or academic environments. Follow-up interviews with participants also were used to confirm or refute the heuristics identified in the field and to further understand the history behind a heuristics development. Furthermore, throughout data collection and analysis, the ethnographer consulted two other engineering education researchers with experience conducting ethnographic research and studying engineering concepts. These consultations added credibility to the findings by allowing external experts an opportunity to challenge the ethnographer's interpretations of the data throughout the research process (Walther et al. 2013).

Findings

The authors identified two different types of heuristics being applied in both environments: practice-based heuristics, and profession-based heuristics. The authors define practice-based heuristics as heuristics that an engineer, company, or department develops over time based on the sociomaterial contexts within which they frequently operate from their experience designing similar structures. These types of heuristics may not be universal to other projects and/or structures with which the engineer, company, or department is less familiar, and therefore may differ from other engineers', companies', or departments' practice-based heuristics. The authors define profession-based heuristics as heuristics a profession has developed over time that are grounded in the sociomaterial contexts of fundamental structural engineering concepts. These types of heuristics are more likely to be transferable across environments and from project to project. Practice-based heuristics were observed mostly in the workplace environment, and rarely were presented in the academic environments. Profession-based heuristics, on the other hand, were prevalent in both environments.

The following subsection presents some of the practice-based heuristics encountered in the workplace environment with a similar practice-based heuristic presented in one of the academic environments. The subsequent subsection then presents some of the profession-based heuristics represented in the academic environments and their relevancy to the sociomaterial contexts of the workplace environment studied. Thus, the heuristics presented in the following sections were chosen to represent heuristics that were more-or-less unique to specific contexts to illustrate this main distinction between practice- and profession-based heuristics.

Practice-Based Heuristics

In the first week of the internship, the ethnographer was tasked with designing additional framing for a roof to support new HVAC equipment being added on the roof. This additional framing would transfer the load of the HVAC equipment into the existing roof framing. The ethnographer asked the engineer who assigned this task for a reasonable assumption of the existing roof dead load with which to begin their calculations. The engineer explained that the dead load for the existing roof framing was 15 psf (0.72 kPa), and that this was one of their firm's "lineages of ideas." The engineer proceeded to explain the meaning of lineages of ideas as standards of practice that an agency develops over time for frequently encountered problems. The engineer then explained that their firm frequently designs these types of structures and has come to learn that a 15-psf (0.72-kPa) dead load for roof materials and framing is an appropriate load estimate.

In a subsequent design task the following week, the ethnographer assumed 15 psf (0.72 kPa) for a roof dead load based on the firm's lineages of ideas. The same engineer asked how the ethnographer determined that dead load value when checking their calculations. The ethnographer explained that they had assumed it based on what the engineer had previously told him about the firm's lineages of ideas. The engineer replied that 15 psf (0.72 kPa) was an acceptable assumption, but that the ethnographer should understand where that magnitude came from. The engineer then proceeded to print a material weights reference sheet that listed dead loads for components that make up roof and ceiling systems. The engineer explained that the roof and ceiling of the structure they were looking at likely consisted of 3-15 and 1-90 lb composition roofing [2.2 psf (0.11 kPa)], 5/8-in. (1.59 cm) OSB sheathing [2.0 psf (0.10 kPa)], asphalt shingles [2.5 psf (0.12 kPa)], glass wool insulation [0.1 psf (0.005 kPa)], and 5/8-in. (1.59 cm) gypsum board ceilings [2.8 psf (0.13 kPa)]. These components all added up to 9.6 psf (0.46 kPa), and the engineer said that the remaining ~5 psf (~0.24 kPa) covered the existing framing and mechanical, electrical, and piping (MEP) equipment. In a subsequent interview, the same engineer noted the origin of the material weight reference sheet:

> I don't keep it in my head what different building materials weigh, but kind of some sheets. I think the one sheet we use is actually from a TJI manual that someone photocopied, you know, 20 years ago, that pretty much everyone in the department uses.

The engineer implicitly referred to using the sheet as a heuristic because it allows him to not have to remember the weight of different building materials. The overall approximate 15 psf (0.72 kPa) dead load demonstrates how the firm developed a practice-based heuristic of estimating roof and ceiling dead loads based on the sociomaterial contexts of a Truss Joist I-Joist (TJI) manufacturer's manual that has continued to work well for the TJI roof structures the firm frequently encounters in design. This is a practice-based heuristic because it was developed over time from the firm's practice-based experience, and is not necessarily an appropriate assumption for all roof/ceiling structures, and may not be what another company would use or develop in their own practice.

The firm also developed some other practice-based heuristics for common conservative load estimates to account for unknown changes that might emerge after the initial design phase of a project. For example, when designing roof trusses for certain structures, they accounted for the addition of a 500-lb (2.22-kN) floating point load acting within 6 in. (15.2 cm) of any joint (i.e., panel point) of a truss after installation to account for increases in load such as additional HVAC equipment being installed. If the point load had to occur at a location along the truss greater than 6 in. (15.2 cm) from any panel point, an additional angle member on each side of the joist had to be provided for additional framing per one of the firm's previously developed details (Fig. 1).

In one instance during the fourth week of the internship, the ethnographer responded to a contractor submittal wherein the contractor was a joist manufacturer with their own specification limiting concentrated point loads to 3 in. (7.62 cm) away from panel points without installing additional bracing (Fig. 2). The ethnographer asked an engineer (Engineer 1) about this discrepancy in the firm's detail and the contractor's specification. Engineer 1 suggested they ask a more-senior engineer (Engineer 2) where their firm's 6 in. (15.2 cm) specification had originated. Engineer 2 was not certain how that specification had originated, but said that it likely came from a previous joist manufacturer's specification. Engineer 1 suggested updating their standard detail to 3 in. (7.62 cm) because of the small angles that were used in their detail. Engineer 2 said that they were comfortable with their detail as it was, but agreed to update their detail to 3 in. (7.62 cm) and then

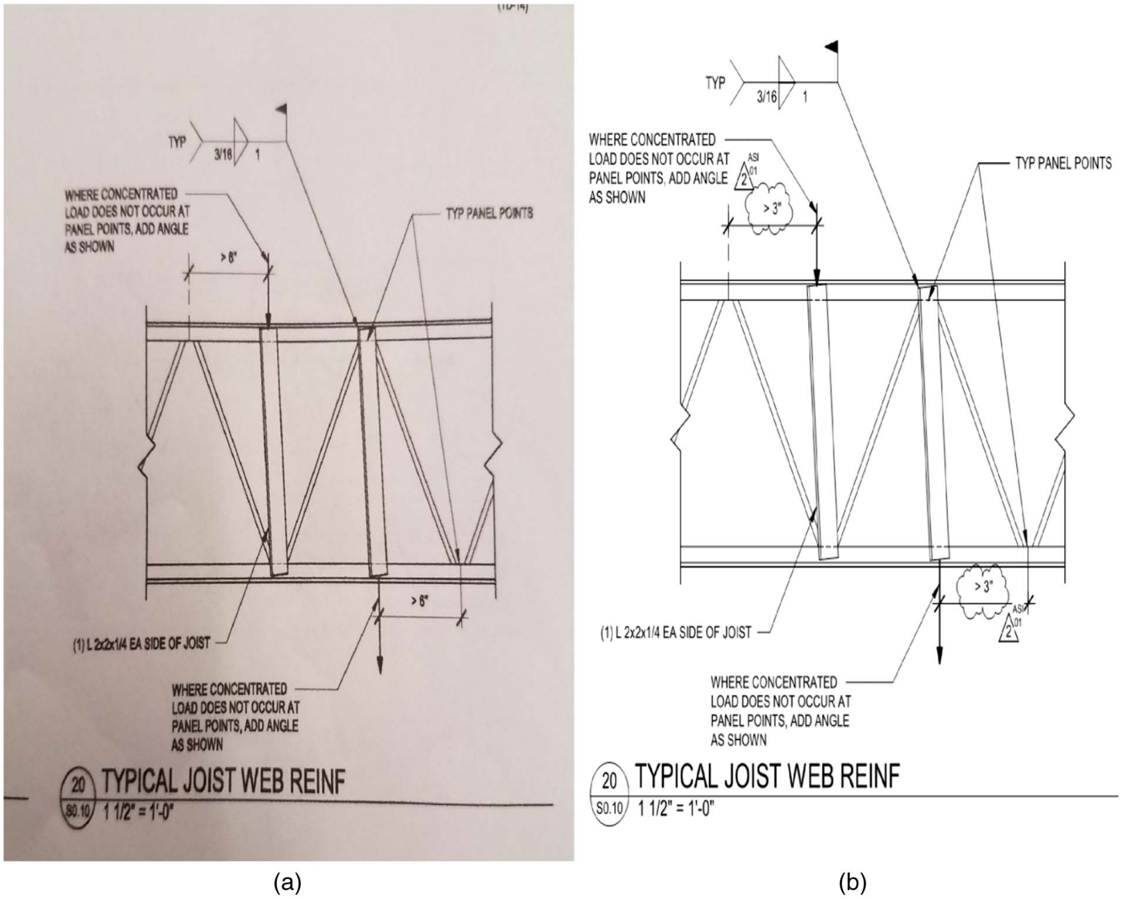

Fig. 1. Change from 6 to 3 in. (15.2 to 7.62 cm) of distance a concentrated load can be applied from a panel point without additional bracing (a) previous standard detail; and (b) updated standard detail.

NOTED ITEMS	COMMENT
Detail [redacted] gives the project limits for concentrated loads resisted by joist chords before adding field installed strut reinforcing. The detail permits a greater distance from panel points than [redacted] standard 3" away. [redacted] recognizes that the specifying professional authorizes concentrated loads located up to 6" away from panel points to govern field installed reinforcing requirements as shown on the detail. Localized chord bending from concentrated loads within 6" will not be analyzed considering insignificant local chord flexure effects. Concentrated loads not specified and located are understood to be a confined accumulation of the represented uniform loads or small point loads already considered in the joist sizing.	Acceptable. We will revise detail to match [redacted] standards.

Fig. 2. Contractor's noted item in submittal and ethnographer's comment.

joked that it eventually will become 2 in. (5.08 cm) based on some other joist manufacturer's specification in the future. Although the joist manufacturer likely based their 3 in. (7.62 cm) limit on performance testing of their trusses, the engineering firm's decision to adopt this specification into their standard details was an example of a heuristic based on the two engineers' judgment about how far from a panel point a concentrated load safely can be applied before additional bracing is needed. The firm originally had developed a standard detail based on a previous manufacturer's product literature, which historically had worked for them, but decided to update their detail and establish a new practice-based heuristic to reflect a more conservative design influenced by the sociomaterial context of another manufacturer's specification.

The firm's development of standard details in general is another example of a practice-based heuristic because they frequently use the standard details they have developed over time to handle common configurations of structural elements. The performance and load path for these standard details are well understood for the types of structures the firm frequently designed. Therefore, these standard details were practice-based heuristics for expediting commonly designed details that likely are different from the standard details developed within the sociomaterial contexts of another company's frequent projects.

Practice-based heuristics were observed less in the academic environments, but one similar scenario of a load estimate assumption emerged in a recitation exercise for the Steel Design course during the second week of the term. In this recitation assignment, students were asked to quantify the dead load acting on columns supporting a typical floor and roof for a given structure. The students were given some of the components contributing to the dead load acting on the columns and were expected to determine the magnitudes of the remaining components contributing to the dead load (Fig. 3). The students were told that, for the column dead load underneath a typical floor, a common estimate for mechanical, electrical, and piping equipment was 10 psf (0.48 kPa), and, similarly, for the column dead load underneath the roof, they were told to assume 10 psf (0.48 kPa) for the MEP and ceiling system. The instructor was asked in a subsequent interview where this heuristic (assumption) originated, to which the instructor replied:

> It depends. This is one of those things where the loads vary depending on company to company. Companies are going to … they're going to make different assumptions for that,

PROJECT: STEEL BUILDING DESIGN CASE STUDY SUBJECT: COLUMN DEAD LOAD TAKE OFF	SHEET 6 of 131

LOAD TABLE - COLUMN DEAD LOAD (LB/FT^2)

COLUMN DEAD LOAD UNDERNEATH TYPICAL FLOOR (LB/FT^2)	
SLAB (4-3/4" Light WT. Concrete) (Lightweight Concrete Density = 96 PCF)	38
MECH./ELEC./PIPING (common practice = 10 psf)	10
CEILING SYSTEM (Table C3.1-1a, ASCE 7-16) (Acoustical fiber board & Mechnical Duct allowance)	5
JOISTS (Assume 11 LB/L.F. @ 3' O.C.)	3.7
GIRDERS (Assume 85 LB/L.F. @ 36' O.C.)	
COLUMNS (36'*30' = 1080 FT.^{2}) (Assume 150LB./L.F.* 13')/1080FT.^{2}	1.8
COLUMN TOTAL DEAD LOAD - TYPICAL FLOOR (LB/FT^2) =	

LOADS FROM
Slab
Mech./Elec./Piping
Ceiling System
GO TO
Joists
Girders
Columns

COLUMN DEAD LOAD UNDERNEATH ROOF (LB/FT^2)	
ROOF DECK (Table C3.1-1a, ASCE 7-16) (Metal, assume 18 gage for estimate)	3
RIGID INSULATION (Table C3.1-1a, ASCE 7-16) (2" thick) 0.75 psf per 1/2"	
MECH./ELEC./PIPING & CEILING SYSTEM (Assume 10 psf)	10
ROOFING (Table C3.1-1a, ASCE 7-16) (Five-ply felt & gravel)	
JOISTS (Assume 11 LB/L.F. @ 3' O.C.)	3.7
GIRDERS (Assume 85 LB/L.F. @ 36' O.C.)	
COLUMNS (36'*30' = 1080 FT.^{2}) (Assume 150LB./L.F.* 13')/1080FT.^{2}	1.8
COLUMN TOTAL DEAD LOAD - ROOF (LB/FT^2) =	

LOADS FROM
Rigid Insulation
Roof Deck
Mech./Elec./Piping
Roofing (felt & gravel)
GO TO
Joists
Girders
Columns

Fig. 3. Recitation exercise for determining total dead load acting on columns.

because you know it somewhat depends on what the occupancy category of it, say a warehouse versus an office building.

Here, the instructor demonstrated that this heuristic of assuming 10 psf (0.48 kPa) for MEP equipment is a practice-based heuristic that varies depending on the sociomaterial contexts of the different companies and the nature of the project.

Profession-Based Heuristics Applicable Across Multiple Contexts

In the Structural Theory II course, students frequently were asked to derive equations for determining the displacements and support reactions for determinate and indeterminate structures. Following the derivation of these equations, students were permitted to use the profession-based heuristic of beam tables so as not to have to derive an equation each time it was needed. For example, in a recitation assignment during the fourth week of the term, the students were asked to use the force (i.e., flexibility) method to derive the equation for the magnitude of the fixed-end moments for a beam fixed at both ends with a concentrated load at midspan (Fig. 4). The students were informed that they could check their derivation with the beam tables in the back of their textbook (Fig. 5).

Following this exercise, students were permitted to refer to the beam tables provided in their course notes and textbook to solve displacements and support reactions on more-complicated

Problem 1
Using the force method, determine the fixed-end moments for the beam in the figure below.

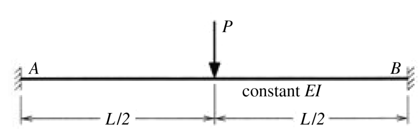

Fig. 4. Recitation problem from the Structural Theory II course.

indeterminate structures. Similar beam tables exist in design aids such as the AISC *Steel Construction Manual* (AISC 2017), which an engineer from the workplace mentioned in an interview as a heuristic that he and other engineers frequently used:

> The steel manual we just go to because it's so easy to identify beam loading, and we use beam loading all over the place, and various combinations of beam loading. So that's one we use all the time. And only in my career have I started using the tables and the actual manual.

These beam tables thus are a profession-based heuristic because they are theoretically based equations for exact solutions that avoid the burden of deriving the equation each time it is needed. In both settings they are represented within the material contexts of design aids such as the course textbook and the *Steel Construction Manual* with the implied social context that structural engineers know how

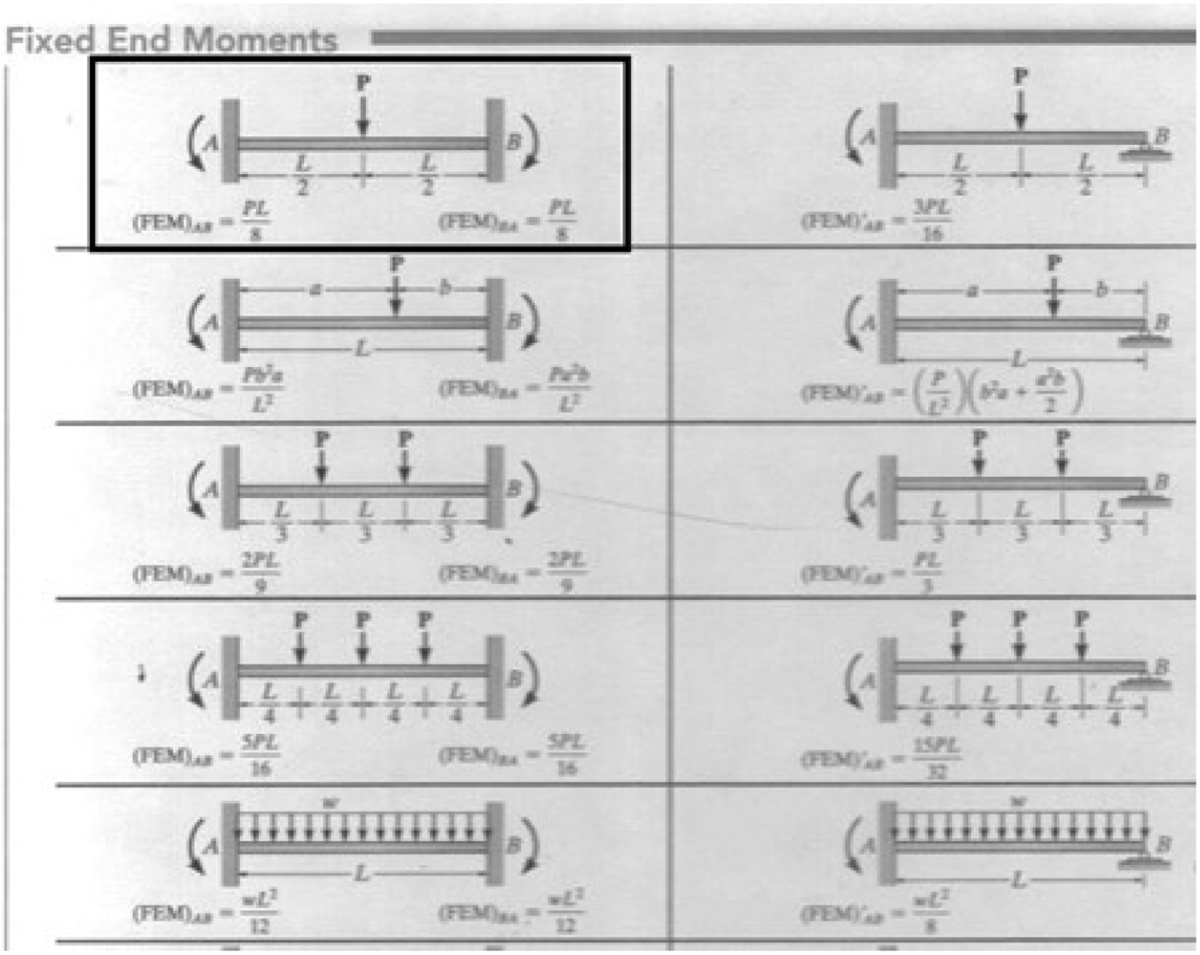

Fig. 5. Back cover matter reprinted from *Structural Analysis, 10th ed.* (Reproduced with permission from Hibbeler 2018.)

to apply these equations appropriately before using them as heuristics. Such heuristics that are observable in similar sociomaterial contexts across multiple environments are indicative of the heuristic being profession-based.

An example of a profession-based heuristic presented in another course that has theoretical underpinnings but does not provide exact solutions is the portal method used to analyze the demand of lateral loads on building frames. In the Structural Theory I course, students were presented this method in lecture examples, handouts, and in homework and recitation problems. Fig. 6 shows a lecture handout provided to students during the seventh week of the term that illustrates the premise of the portal method.

The method requires students to draw the deflected shape to identify inflection points in the columns and beam(s) where hinges can be assumed to be located. This provides an additional equilibrium equation for each assumed hinge that then can be used to approximately analyze the original indeterminate structure as a determinate structure using equilibrium equations. The portal method and other approximate analysis methods can be defined as profession-based heuristics because they rely on fundamental concepts of engineering mechanics (e.g., zero internal moment at inflection points) and equilibrium to approximately analyze structures before using and/or to check more-exact analysis methods (Hibbeler 2018). The instructor for this course frequently emphasized the value of this and other approximate analysis methods

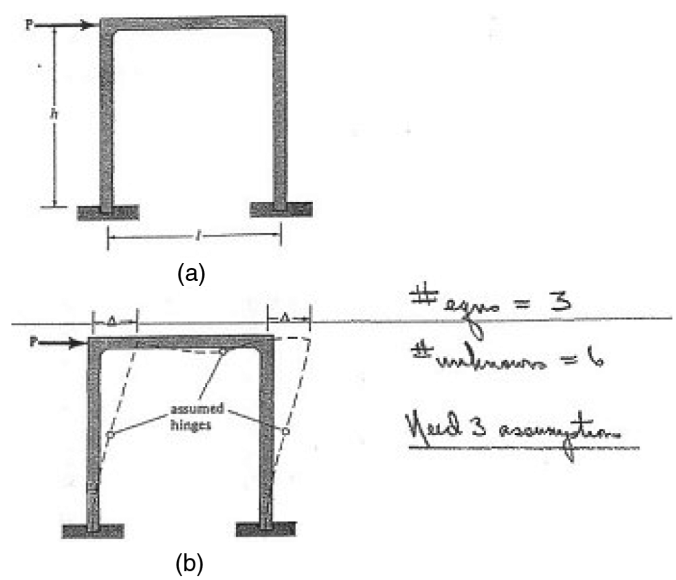

Fig. 6. Illustration of portal method assumption of hinge formation in the inflection points of the frame's deflected shape. Modified from *Structural Analysis, 10th ed.* (Reproduced with permission from Hibbeler 2018.)

Problem 2: a) Compare ϕM_n for singly reinforced rectangular beams having the following properties:

Beam No.	b (in)	d (in)	Reinforcing Bars	f'c (psi)	fy (ksi)
1	12	24	3-#10	4000	60
2	12	24	3-#10	4000	**40**
3	12	24	3-#10	**5250**	60
4	12	24	**2-#14**	4000	60
5	12	**40**	3-#10	4000	60
6	**24**	24	3-#10	4000	60

b) Taking Beam No. 1 as the reference, discuss the effects of changing, A_s, f_y, f'_c, d, and b on the design strength.

c) What is the most effective way to increase ϕM_n? What is least effective?

Fig. 7. Homework problem from the reinforced concrete design course.

within the sociomaterial contexts of schematic design before member sizes are known and/or as a tool for checking software output.

In Week 3 of the Reinforced Concrete Design course, the instructor provided students with a homework assignment that asked them to determine the moment capacity of multiple different beams and determine which design properties contributed the most and the least to increasing the moment capacity of a RC beam (Fig. 7). Upon completion of the assignment, students were expected to identify beam depth (d), steel rebar yield strength (fy) and the cross-sectional area of the reinforcing bars (As) as the design properties that have the biggest impact on moment capacity, whereas beam width (b) and concrete strength (f'_c) have the least impact. This provides students with a heuristic for quickly assessing how changes to certain design properties impact a RC beam's flexural capacity. This heuristic can be considered profession-based because it is based on the fundamental concepts used in RC design (equilibrium and strain compatibility) and in engineering mechanics (second moment of area), and therefore is transferable across companies and projects.

In an interview, an engineer in the workplace environment emphasized this transferability of profession-based heuristics:

> I tend to focus on big-picture things. I also think it's the most transferable across projects, so I'm always focusing on … I care less if it's what specific beam size it is or I got a #9 rebar and more like what order of magnitude change did this other change cause. So if the architect changes an opening size or span, I'm like, well, what does that change in percentage of your load? Is it a 5% delta? Because that's not a big change. Is it 200%? That's a big change. And that's the sort of stuff you can remember without having to remember specifics, and you can use that stuff in client meetings and meetings with consultants to kind of guide discussion, and it's less, nobody really wants you to, I mean it's impressive when you can rattle off a beam size and like, "Oh yeah. That's gonna be an 18 by 30." … But whereas if you can say, "Yeah. If you change that, that's gonna double your load or double what we have to do." You aren't necessarily locking yourself into an answer but you still understand what's going on.

In this excerpt, the engineer never explicitly mentioned heuristics, but referred to "big-picture things" as being "the most transferable across projects" and "that's the sort of stuff you can remember without having to remember specifics." Similar to the homework assignment in Fig. 7, the purpose was not to know how a specific beam size or rebar size will perform, but to grasp how changing these things influences the big picture of a design. That way, in the sociomaterial context of an architect wanting to increase floor height, thereby reducing beam depth, the students can draw upon this profession-based heuristic to know that it will considerably alter the beam capacity and require a possible redesign.

Discussion

Previous research has noted that engineering students are uncertain about using engineering judgment and find this judgment difficult to develop (Koch et al. 2010; Wirth et al. 2017). Engineering judgment has been defined as "common sense," a "sense of proportion," or "a sense of what is important" (Vick 2002), and it can be considered a heuristic used for assessing alternatives and developing appropriately conservative estimates (MacRobert 2018). This study's description of heuristics as being practice-based or profession-based contributes to previous research on the education of heuristics, such as engineering judgment, by distinguishing how certain types of heuristics can have the most utility for students in their undergraduate engineering education. For example, Gainsburg et al. (2010) noted that structural engineers' knowledge of rules of thumb and estimates predominantly was formed from their practical experience, as opposed to in their formal education. Furthermore, Gainsburg et al. (2010) noted that majority of the knowledge they observed structural engineers using was practice generated, rather than being historically established knowledge within the profession. Gainsburg et al. (2010) claimed that these findings provided "empirical justification for modifying traditional university curriculum, reducing some of the emphasis on theory and other historically established information to make room for more practical learning" (p. 36).

Profession-based heuristics, however, still have educational value to students because their use is less dependent on the sociomaterial contexts of a specific project or individual company's standard of practice. Although the universality of profession-based heuristics across academic and workplace environments make these heuristics appealing for bridging the education-practice gap, existing research suggests that student understanding of such heuristics can be primarily procedural, with little understanding of the fundamental concepts underlying a profession-based heuristic that makes it applicable to novel contexts (Chi et al. 1981; Tarabon et al. 2007). One recommendation for resolving this concern is for instructors to emphasize frequently the underlying concepts of a profession-based heuristic and expose students to multiple unique scenarios in which it can be applied. For example, providing students with practice with approximate analysis techniques such as the portal method in Fig. 6 involving a variety of structural configurations and load patterns might help students develop judgment about how structures displace and where hinges form so that they learn how to apply such a method when encountering unique structural configurations in the workplace. The homework problem for the Reinforced Concrete Design course (Fig. 7) is another profession-based heuristic that provides students with an intuitive sense of how significantly certain design parameters influence an overall design. Ruddy and Ioannides (2004) provided several profession- and practice-based heuristics for steel design that also can be used to foster students' judgment about the steel design parameters that matter most in schematic design.

The utilization of practice-based heuristics is more contentious, based on their relevance to a specific problem, project, firm, or working group. The differences between practice-based and profession-based heuristics are symbolic of the divide between academic and workplace settings. Engineering curricula largely focus on fundamental concepts, with some presence of profession-based heuristics and little or no practice-based heuristics. The base assumption is that if students know the concepts well, they will be able to apply them in practice (Aparicio and Ruiz-Teran 2007; Balogh and Criswell 2013; Robertson 2002; Streveler et al. 2008). Situated cognition theory in its most basic form fundamentally opposes this approach, arguing that all knowledge is embedded in a surrounding context, and that learning should occur in authentic practice or simulations of that practice (Brown et al. 1989; Johri et al. 2014; Lave and Wenger 1991). The differentiation between profession-based heuristics and practice-based heuristics provides a way to describe heuristics that are more-or-less transferable to different environments. Practice-based heuristics are more dependent on the sociomaterial contexts of a company's or department's standards of practice and frequently encountered engineering problems, and therefore likely are less transferable across environments. If the base assumption of higher education involved situated cognition rather than foundational understanding of concepts, then practice-based heuristics should be prevalent in the curriculum.

We suggest that infusion of additional practice-based heuristics would be a positive addition to the curriculum. The existing curriculum is very concept heavy, so leaning toward a more practice-oriented curriculum at least would acknowledge more holistically situated cognition and practice-based approaches. Considering a practice-based heuristic to be specific to a firm, one could argue that knowledge is relevant only to that firm. However, practice-based heuristics represent authentic and embedded engineering knowledge, and therefore are symbolic of engineering practice. Essentially, they provide a glimpse of engineers' ways of thinking. Thus, understanding how practice-based heuristics are developed within certain contexts offers a window into a practicing engineer's problem-solving process and a synthesis of their practical experience, engineering judgment, and fundamental conceptual understanding when solving a unique problem. Instructors could ask their students to develop and justify their own heuristics for solving unique and/or more-open-ended problems as a potential vehicle for applying fundamental concepts and fostering within students an engineer's way of thinking that would be more transferable to the workplace than the heuristic itself.

If heuristics are used in curriculum, it is suggested that they include instruction about what heuristics are and their role in engineering practice. Certain practice-based heuristics may be more common across companies and projects, but instructors should clarify whether a heuristic presented in the classroom is practice- or profession-based, and should note the limitations and potential errors of applying more-or-less universal heuristics without consideration of the contexts in which they were developed. There may be value in a course or courses specifically on engineering heuristics, with the goal of orienting students to learning authentic techniques and approaches, and also learning about the background and limitations of these approaches. This would align with broader educational goals of critical thinking and evaluation. Alternatively, students could be exposed to practice- and profession-based heuristics through case studies of actual projects. The benefit of teaching heuristics through case studies is that each case is situated in specific social and material contexts, allowing the opportunity for students to identify heuristics specific to the case and heuristics that can be applied more broadly to other engineering problems (Gainsburg et al. 2010; Prince and Felder 2006).

Future research could investigate which heuristics are used the most by practicing structural engineers for solving specific types of problems and why, in order to identify the practice- and profession-based heuristics that are most applicable to structural engineering practice and the role they play in design. Additionally, investigating more holistically the role of practice- and profession-based heuristics in curricula and in student learning would help guide structural engineering instructors in implementing heuristics.

Conclusion

This research explored how heuristics were represented within the sociomaterial contexts of a structural engineering workplace and academic environments. Although previous research has demonstrated the value of heuristics in structural engineering for handling complex, real-world problems, little to no research has explored the sociomaterial contexts of the workplace and academic environments to gain a deeper understanding of how these contexts influence the development and application of certain types of heuristics. The use of ethnographic methods allowed for an in-depth exploration of both a workplace and academic environments, which led to the identification of two different types of heuristics. Practice-based and profession-based heuristics provide a framework for identifying heuristics that are more and less dependent, respectively, on the context of their application. Heuristics, overall, previously were considered to be prone to error because of their context dependency; however, both profession-based and practice-based heuristics provide unique opportunities for engineering education to connect fundamental concepts with pragmatic approaches and an engineering way of thinking that are relevant to the sociomaterial contexts of practice. Future research could consider the use of similar ethnographic methods for exploring other discipline's heuristics and could identify more broadly how practice- and profession-based heuristics used in workplace environments can be integrated into engineering curricula.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data), including, but not limited to field notes, images of artifacts, and interview transcripts.

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