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The honeycomb of engineering framework: Philosophy of engineering guiding precollege engineering education

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Abstract

Background: Understanding the nature of engineering is important for shaping engineering education, especially precollege education. While much research has established the pedagogical benefits of teaching engineering in kindergarten through 12th grade (K–12), the philosophical foundations of engineering remain under-examined.

Purpose: This conceptual paper introduces the honeycomb of engineering framework, which offers an epistemologically justified theoretical position and a pedagogical lens that can be used to examine ways engineering concepts and practices are taught in precollege education.

Scope/Method: The honeycomb of engineering was developed as a descriptive framework by examining existing literature over a wide range of related disciplines such as the philosophy of engineering and technology, as well as design thinking and practice. The pedagogical translation of the framework was then developed to examine published precollege engineering curricula.

Results: The framework categorizes the multiple goals of engineering using an ontological classification of engineering inquiries anchored in the central practice of negotiating risks and benefits (i.e., trade-offs). This framework also illustrates the adaptability of design methodology in guiding six inquiries: (1) user-centered design, (2) design-build-test, (3) engineering science, (4) optimization, (5) engineering analysis, and (6) reverse engineering. The published curricula represented these inquiries with varying degrees, with design-build-test lessons seeing the most representation followed by user-centered design.

Conclusions: The honeycomb of engineering framework delineates variations in engineering education based on an epistemological explanation. The pedagogical translations offer guidance to educators, researchers, and curriculum designers for differentiating curricular aims and learning outcomes resulting from participation in different engineering inquiries.

KEYWORDS

design-build-test, engineering analysis, engineering science, epistemology, honeycomb framework, K–12, optimization, precollege, reverse engineering, user-centered design

1 | INTRODUCTION

As a subject, engineering initially entered the public school education curricula in the late 1900s under the auspices of technology education (Heywood, 1993). The early 2000s have witnessed added explicit references to engineering in kindergarten through 12th grade (K–12) education discourse with an increased interest in introducing and integrating it in the early years of schooling (C. Cunningham & Lachapelle, 2007; Mousoulides & English, 2009; National Academy of Engineering & National Research Council [NAE & NRC], 2009; Rogers & Portsmore, 2004). In parallel to these efforts highlighting the importance of precollege engineering education, design-based learning has emerged as an alternative to inquiry-based science education, with curricular models featuring the pedagogical utility of design as a central focus (Fortus et al., 2005; Kolodner, 2002; Mehalik et al., 2008). Added to these initiatives was the concept of integrated science, technology, engineering, and mathematics (STEM) education, a pedagogical approach that uses design challenges to teach STEM in an interconnected and meaningful way (Bryan et al., 2015; Daugherty & Carter, 2018; Mustafa et al., 2016; Stohlmann et al., 2012).

These efforts have yielded promising findings illustrating the importance of engineering and design in K–12 education. Most of these studies have argued for the pedagogical role of design in supporting student thinking and learning (Li et al., 2019) in science, engineering, and mathematics (C. M. Cunningham et al., 2020; T. R. Kelley & Knowles, 2016), as well as other areas, such as language and literacy (Dorie et al., 2013). However, while research promoting the pedagogical benefits of engineering and design has grown in promising ways, neither research demarcating different types of engineering inquiries nor studies with an epistemological justification for precollege engineering education have grown at the same rate (C. M. Cunningham & Kelly, 2017; Pleasants & Olson, 2019). This conceptual paper aims to address this gap by proposing a framework based on the philosophical foundations of engineering, technology, and design. A pedagogical translation of this framework can then be developed to guide precollege engineering education. The focus here is on precollege engineering education, where there is an urgent need to distinguish the pedagogical motives from the philosophical underpinning of the engineering discipline (Purzer & Quintana-Cifuentes, 2019). The resulting outcome of this effort is the honeycomb of engineering framework.

This article features two major sections. The first section justifies the need for a framework and presents a multifaceted characterization of engineering based on a synthesis of definitions from existing literature. Next, the structure and guiding principles of the honeycomb of engineering framework are outlined and explicated with its six engineering inquiries: user-centered design (UCD), design-build-test (DBT), engineering science (ENS), engineering optimization (OPT), engineering analysis (EAN), and reverse engineering (REV). The second section presents the pedagogical translation of the framework and example lessons from published K–12 curricula, followed by an analysis of the prevalence of the six inquiries outlined in the honeycomb framework. Discussion and conclusions reiterate that the honeycomb of engineering framework is grounded on a multifaceted definition of engineering and uses this epistemological justification to inform precollege engineering education.

2 | SECTION I: A FRAMEWORK BASED ON ENGINEERING PHILOSOPHY

Engineering and philosophy may appear to be two distinct fields, yet there is much they can contribute to each other (Bucciarelli, 2003; Heywood, 2011; Mitcham, 1998). Research on the epistemology of engineering is essential to the field of engineering education because a philosophical perspective can provide conceptual clarification of terms and concepts, better articulation of epistemic practices, and tools for critiquing existing definitions and assumptions (Vries, 2005). Such conceptual clarification, including a nuanced definition of engineering, offers heuristic value for educators by providing pedagogical guidance and insights (Bucciarelli, 2003; Martin, 1974). Similar to how a conceptual framework guides research and methodological procedures, a conceptual clarification can guide curricular decisions and pedagogical approaches (Ponce et al., 2017).

Moreover, a framework based on the philosophical foundation of engineering would not only benefit engineering education efforts at all levels but especially precollege education where the disciplinary and epistemological purposes intersect with pedagogical reform calling for interdisciplinary and holistic education. Without epistemological clarity to guide educators and students, concepts can be misinterpreted (Carberry, 2014). Hence, it is no surprise that there is widespread criticism of the variety of integration methods and curricular quality in STEM education (Akgündüz, 2018; English, 2016; Moore et al., 2014). The integration of engineering into K–12 education has been led by researchers from diverse disciplinary backgrounds and epistemological views, naturally leading to differences in their integrated STEM education approaches. Applying a philosophical lens to precollege engineering education would provide conceptual clarification with a more refined definition of engineering and explain curricular variation from a fresh perspective. Instructional decisions could then be examined and guided via better definitions, better articulation of epistemic practices, and better assumptions.

Given these considerations, this article argues for an engineering philosophy-driven framework and presents the honeycomb of engineering framework, the development of which has emerged from the need to define engineering and its philosophy comprehensively. Furthermore, the framework's pedagogical translations aim to explain ways of integrating engineering in K–12 education.

3 | COMPARING THE HONEYCOMB OF ENGINEERING TO OTHER FRAMEWORKS

Two notable existing frameworks are comparable to the honeycomb of engineering. The first, the Framework for P–12 Engineering Learning, was developed through the collaborative efforts of the Advancing Excellence in P–12 Engineering Education research collaborative and the American Society for Engineering Education (AE3 & ASEE, 2020). Their framework aims to transform educational policy with a vision of including engineering and engineering technology as a compulsory school subject. The design of this comprehensive framework for P–12 engineering education starts with a taxonomy of engineering content as a dimension of engineering literacy (Strimel et al., 2020). This taxonomy, which emerged from a modified Delphi study with a focus group of expert panels, including K–12 teachers, university professors, and industry professionals, outlines engineering knowledge (such as statics and circuit theory), engineering practices (such as design and materials processing), and engineering habits of mind (such as optimism and creativity).

The second, the Framework for Quality K–12 Engineering Education developed by Moore et al. (2014), is an evaluative framework specifically focusing on engineering curricula. This framework is based on an examination of ABET's criteria for engineering accreditation of higher education institutions; content analysis of K–12 science, mathematics, and technology standards in different US states; and an extensive review of literature on engineering and education. Their framework, being evaluative, has a particular focus on appraising and guiding the quality of curricula in STEM integration efforts.

Unlike these two frameworks, the former transformative and the latter evaluative, the honeycomb of engineering is a descriptive framework. It does not aim to transform engineering education but rather to provide a language for a more nuanced representation of engineering in its curricular translations. Similarly, the honeycomb framework does not aim to evaluate quality but instead seeks to explain curricular variations from the perspective of the philosophy of engineering. Hence, the honeycomb of engineering framework complements the existing efforts working toward a common goal of improving precollege engineering education.

4 | CENTERING ON THE MULTIFACETED NATURE OF ENGINEERING

Engineering is a multifaceted discipline by nature of its epistemology, methodology, and ethical values. There is no one type of engineering, as there is no brief definition of engineering that is satisfactory (Radder, 2009; Trevelyan, 2021). Definitions are an important part of the conceptualization of a discipline, yet philosophers of engineering have struggled to define engineering (Grimson & Murphy, 2015). One popular definition, the application of science and mathematics to solve problems, is critiqued by scholars as being narrow (Alza, 2017; Figueiredo, 2008). At the other extreme, engineering is also defined as the process of transforming a given state of materials or affairs to the desired state under uncertainty (Simon, 1981), a definition that is seen as being too abstract.

We sought a nuanced definition of engineering, one in line with perspectives proposed by philosophers of engineering and many engineering educators (for detailed discussions, see Dixon, 1966; Figueiredo, 2008; Froyd et al., 2012; Kant & Kerr, 2019; Meijers, 2009; Trevelyan & Williams, 2019; Vinck, 2019; Vries, 2016). We reason that a discipline is defined by the types of problems it addresses, not simply by its method or in comparison to another discipline (in this case, science). First, the core practice of design is shared across different disciplines and is not unique to engineering (Zimring & Craig, 2001). However, the design methodology is flexible and adaptable. Whether the goal is to create a new technology or improve an existing one, the design methodology can guide different inquiries. Second, engineering tackles multifaceted and multidisciplinary problems, meaning engineers have many roles: problem-solvers, scientists, managers, doers, innovators, and coordinators (Lande et al., 2013; Pawley, 2009; Trevelyan, 2021). Thus, engineering practice requires the knowledge and the skills of science, mathematics, sociology, ethics, and business, resulting in an inherently interdisciplinary nature, as argued by Figueiredo (2008) and Radcliffe (2015).

The typical undergraduate engineering curricula have a strong emphasis on science and mathematics in the early years of undergraduate education (Auyang, 2006; Reynolds, 1992; Seely, 1999). Likewise, primary and secondary education takes a similar approach when justifying the integration of engineering and technology in science education, stating that "it is important for students to explore the practical use of science, given that a singular focus on the core ideas of the disciplines would tend to shortchange the importance of applications" (National Research Council [NRC], 2012, p. 12). As Auyang (2006) states, engineering "amplifies traditional ingenuity by the power of scientific reasoning and knowledge" (p. 1).

Yet, engineering not only applies scientific knowledge but also contributes to the creation of new knowledge, specifically technological knowledge. This aspect of engineering is referred to as the ENSs (Dixon, 1966; Layton, 1974). Engineers also generate new knowledge related to the designed world, and this is where the work of engineers overlaps with the work of scientists (Figueiredo, 2008; Meijers, 2009; Pawley, 2009) in that both depend on mathematics and instrumentation, utilize controlled experimentation, and strive for theory-building (Auyang, 2006). For example, engineers at universities or industry laboratories conduct research to develop new technological knowledge, such as developing stable materials that can be used to make solar cells more efficient and affordable.

Engineering is creation and invention through design, responding to societal needs with technological artifacts. Successful innovation requires consideration of context and the subsequent balancing of social, economic, technical, and environmental factors in design (Rousselot et al., 2012). Trade-off decisions must be negotiated to balance these factors and users' needs and wants. This negotiation of trade-offs is a practice many scholars consider to be central to design (Dym et al., 2005; Lewis, 2006). Hence, engineering design is often described as a creative activity using a systematic approach to optimize within design requirements and constraints (Meijers, 2009; Pahl et al., 2007). In engineering, design methodologies must allow the integration of theoretical knowledge with practical knowledge while creating social and commercial value.

Engineering often involves technical coordination within an enterprise and includes planning, managing, monitoring, and maintaining existing technological systems, not just designing and creating such systems. A common example is the manufacturing and industrial system that requires due diligence and monitoring of quality in a multitude of dimensions such as value, consistency, and reliability, among others (Moen et al., 1991). Trevelyan (2007) cautions that such technical coordination requires technical expertise and must not be labeled as nontechnical or detached from engineering. If not well-managed and maintained, engineering systems carry risks and consequences that could result in accidents and harmful effects (Auyang, 2006). In fact, such work involving the maintenance and repair of existing technological systems is the ordinary and routine work of engineers, although scholars recognize this type of work is often understated in engineering education (Russell & Vinsel, 2018; Trevelyan & Williams, 2019; Vinck, 2019). As Trevelyan and Williams (2019) explain, engineering creates value at the intersection of technical problem solving, scientific discovery, innovation through design, and technical coordination.

The social and contextualized aspects of engineering are extremely vital, yet they are underemphasized in conventional definitions. Scholars such as Bucciarelli (2001) argue that engineering is dependent on "the negotiation of interest and proposals of different participants; hence the process is social and knowledge is socially constructed" (p. 297). According to Bucciarelli (2003), these social endeavors of engineering can be explicated from two perspectives. First, societal context, as well as user and human factors, plays an essential role in engineering (Lewis, 2006; Proctor & Van Zandt, 2018). In fact, this societal utility differentiates engineering from natural sciences. Simply put, engineering transforms society. Second, engineering decisions are the products of social processes. Inarguably, data and evidence are important in engineering (Grimson & Murphy, 2015). However, such data-driven decision-making does not occur in a vacuum; engineering relies on the social process of reviews and evaluations, coordination of human efforts, and collaboration and teamwork, all key practices among engineers. The peer-review process and design review sessions engage clients, supervisors, and peers in negotiation as they reach a consensus when clarifying goals, considering trade-offs, assessing cost and benefits, and reviewing evidence. These social processes that enable discourse, clarification, and recognition of different perspectives, as Trevelyan (2010) argues, are necessary to help reduce risks in engineering projects.

The honeycomb of engineering framework is built on the principle of engineering as a socially constructed process and engineering design as a flexible vehicle for guiding different types of engineering inquiries. This framework is an ontological classification of multiple facets of engineering mapped to the core practice of design and a conceptualization of engineering as the creation, monitoring, management, and improvement of technological systems through the careful negotiation of risks and benefits. As detailed in later sections, the honeycomb of engineering framework specifies six types of engineering inquiry. The social, iterative nature of design is illustrated with a honeycomb representation. The pedagogical translation of the honeycomb of engineering further contributes to explaining variations in engineering education based on the nature of engineering.

5 | THE HONEYCOMB OF ENGINEERING FRAMEWORK

5.1 | The representation of negotiation at the center of the honeycomb

The honeycomb of engineering framework situates the negotiation of risks and benefits at its center, highlighting that communicating and negotiating trade-offs occur at all design stages (see Figure 1). This approach also represents two meta-level facets: design as a reflective practice (Schön, 1992) and design as an iterative process (Adams, 2002). There are no single paths nor perfect solutions—all decisions are negotiated under constraints (budget, time, regulations, among others) and informed by evidence and engineering ethics. The term “negotiation” is selected purposefully to capture the internal and external dialogue that engineers engage in continuously, as supported by Bucciarelli's (2003) articulation of engineering philosophy. Internal negotiation occurs with the self through reflective practices. External negotiation occurs with colleagues through teamwork and discussion, with clients through design reviews, and with

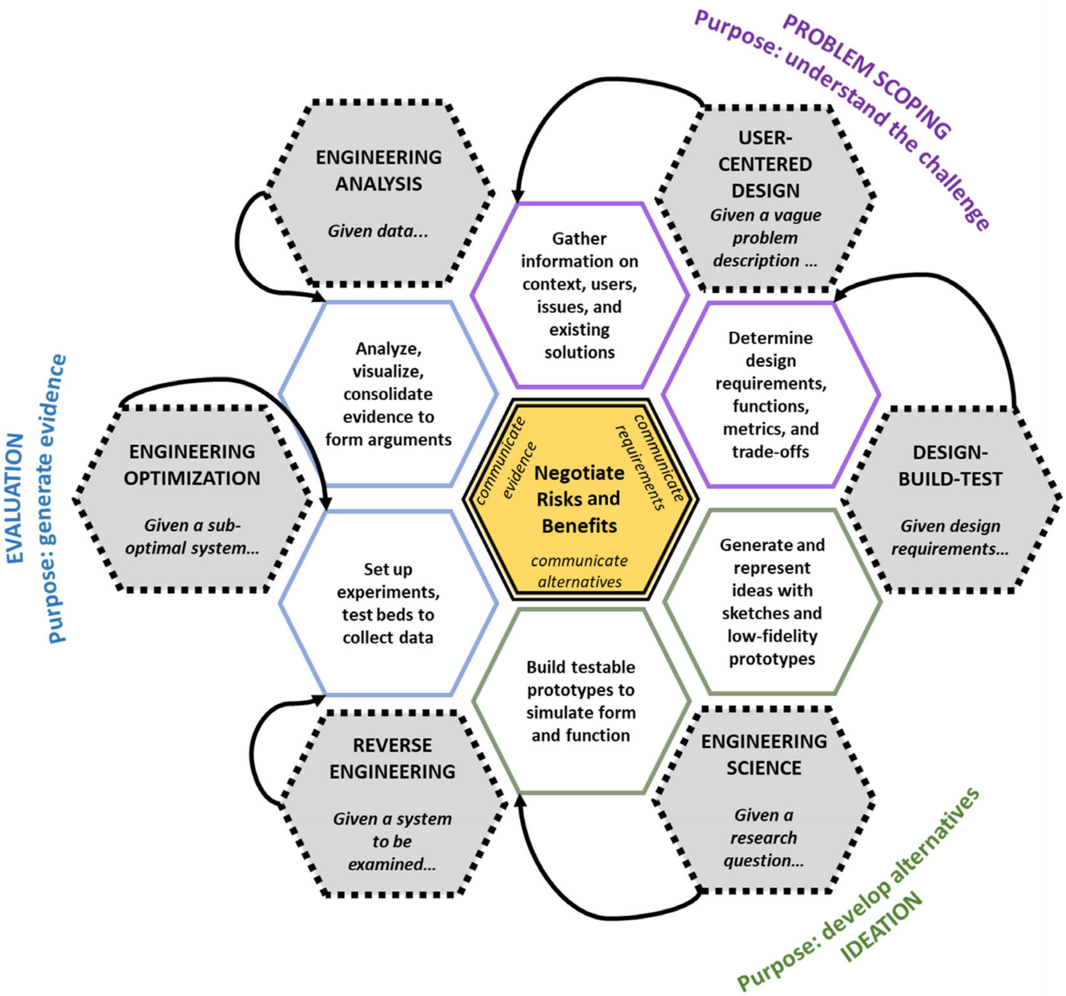

FIGURE 1 The honeycomb of engineering framework (Purzer, 2021) [Color figure can be viewed at wileyonlinelibrary.com]

stakeholders through conversations and feedback. As Trevelyan and Williams (2019) argue, judging anticipated risks and benefits, reducing risks, and preventing inadvertent harm are routine roles of engineers. Effective communication, reliable coordination, and design reviews are essential in ensuring due diligence in analysis, inspections, performance forecasts, and compliance with standards. The perception, quantification, and management of risk and benefits are at the core of how engineers add societal and economic value through their work (for a detailed discussion, see Trevelyan & Williams, 2019).

The design literature includes various illustrations of the design process (Dubberly, 2005), which are often visualized as a flow diagram, a circular loop, or a linear process with iteration paths. These representations are critiqued by some for being simplistic and not representing iterative interactions across stages of design (Oplinger & Lande, 2014). Others, such as Bucciarelli (2003), point to the similarities of these diagrams in representing the design process as mechanistic and lacking an overt representation of people and the critical role of communication between engineers and the many stakeholders they interact with. In some models, the human element is evident with communication of results added as the last step of the design process, and in others, the human-centered aspect of design and cocreation through empathy-building with users are emphasized as a starting point (T. Kelley, 2001; Tschimmel, 2012).

We introduce an alternative, a simple yet comprehensive model that places negotiation and reflective practices at the center of the design (Purzer, 2021). This model also enables the iterations across design stages to occur fluidly through negotiation (see Figure 1). Micro- and macro-iterations occur throughout the design process (Purzer et al., 2015) such that exploring a design idea can lead to a new idea (micro-iteration), or the problem scoping stage can be revisited during the ideation or evaluation stages (macro-iteration). The hexagonal cells facilitate the connections among engineering practices within stages of design. Users of the honeycomb framework start at different cells according to the engineering inquiry they are engaged in and the type of technological knowledge or solutions they seek to produce. They can then move across cells fluently and iteratively using a customized design process. Hence, the practice of negotiating risks and benefits is intentionally located at the core of the honeycomb of engineering framework as the mediator of the adaptable and flexible nature of the design process.

5.2 | The representation of engineering practices in adjoining cells of the honeycomb

Engineering design is often described using the function–structure–behavior model (Gero et al., 1992; Hmelo-Silver & Pfeffer, 2004) associated with the three core practices of problem scoping, ideation, and evaluation (Shiva Kumar et al., 1994). In the honeycomb model, these practices are represented in hexagonal cells connected with the other cells either by proximity or through the central practice of negotiation of risks and benefits.

Problem scoping is the process of defining the problem space and understanding the need. To a novice, problems often appear clear and straightforward (Atman et al., 2007; Nadler et al., 1989). However, the practices associated with problem scoping are complex, including gathering information on the problem context, understanding the needs of the users and other stakeholders, researching existing solutions and their limitations, and explicitly confronting and stating assumptions. In addition, problem scoping involves determining the required design functions, including design criteria, constraints, and metrics that will be used to measure the extent to which these requirements are met. Diverse sources of information are sought and referenced to support problem scoping efforts (Fosmire & Radcliffe, 2013; Macleod et al., 1994). For example, observing user behavior and immersive empathy-building activities are among those strategies used when determining human needs and problems (T. Kelley, 2001; Stacey & Tether, 2015). The designers' understanding of the problem or issue is negotiated and agreed upon within a design team and through communication with the client.

Ideation is the practice of exploring the solution space and the structures of potential solutions. Idea fluency is expected and associated with the creativity and quality of solutions (Jonson, 2005). Designers use specific strategies to avoid fixation and premature decision-making (Crilly & Moroşanu Firth, 2019). In addition, sketches and rapid prototypes are built based on a diverse set of purposes, including to represent and communicate a designer's internal creative reflection (Lauff et al., 2020), as well as to explore and tinker with design ideas (Crilly & Moroşanu Firth, 2019). More elaborate functional prototypes are also built to simulate and test design concepts against functional requirements. Prototypes are necessary not only for ideation but also that data on the performance of design concepts can be collected. Through micro-iterations, these simulations and tests inform refinements and support the generation of new ideas. Through feedback and these refinements, detailed design prototypes are developed. Macro-iterations may be necessary to clarify design criteria or constraints and refine design metrics.

Evaluation is the examination of the behavior of design concepts to verify the performance of design systems and subsystems vis-a-vis the requirements determined during problem scoping (Shiva Kumar et al., 1994). It is the process by which data are generated and used to support arguments and decisions. For example, during evaluation, prototypes are compared based on their performance related to how well they address the design requirements (i.e., design criteria and constraints). Experiments are developed to facilitate testing detailed prototypes for specific functions (e.g., durability) using testbeds and simulations such as finite element analysis (Bailey, 2015). Visualizations of data are used to support arguments and persuade stakeholders (Coulentianos et al., 2020). Evidence gathering involves data analysis and calculations, as well as using information literacy practices (e.g., to estimate material cost) by locating and documenting trustworthy sources of information (Fosmire & Radcliffe, 2013; Gregory, 1982).

The honeycomb representation reflects core aspects of design, as well as the flexible and adaptable nature of design methodology in guiding the multifaceted nature of engineering. As such the honeycomb framework recognizes and embraces different types of engineering inquiries, from developing and inventing new technologies to transforming, managing, and maintaining existing ones.

5.3 | The six engineering inquiries represented in the honeycomb of engineering framework

The honeycomb of engineering framework does not treat design as simply a means for developing new technologies. This framework encompasses the diverse roles assumed by engineers who may be maintaining or inspecting existing technologies, as well as those who design new technologies to provide solutions to various problems. OPT, EAN, and REV are engineering inquiries performed on existing technologies, while UCD, DBT, and ENS are used to develop new technologies. While being comprehensive, the framework is not exhaustive in that it does not claim to cover all inquiries or aspects of engineering. Future research will allow for elaboration and refinement of the honeycomb model.

In the honeycomb of engineering framework, we illustrate six engineering inquiries. The design processes associated with each of the six dimensions of the framework are not prescriptive but rather illustrative of the differing critical foci and starting points of each (see Figure 2a–f). The four core practices of design discussed in the previous section (negotiation, problem scoping, ideation, and evaluation) are either highlighted or muted based on different engineering inquiries. The honeycomb framework emphasizes the negotiation of risks and benefits as a central connector across all categories and practices. The subsequent subsections explicate the epistemological definition of each engineering aspect.

Given the multifaceted nature of engineering, the opportunities for categorization are extensive. The honeycomb of engineering framework targets the following six ontological categorizations, connected through the practices of design:

1. User-centered design (UCD).
2. Design-build-test (DBT).
3. Engineering science (ENS).
4. Engineering optimization (OPT).
5. Engineering analysis (EAN).
6. Reverse engineering (REV).

5.3.1 | Engineering inquiry number 1: UCD

Contextualized, UCD enables problem-solving and innovation by prioritizing the understanding of user needs and stakeholder wants within a specific context or situation (T. Kelley, 2001). Design constraints and criteria are determined through problem scoping, defined as the process of understanding user needs and their context, important because for a design outcome to be effective, these must be met (Lowdermilk, 2013). The design process starts with understanding these needs via observations and interviews, as well as gathering information from other sources knowledgeable about the context. The UCD design process subsequently focuses on framing the problem by understanding the users, either a person or an animal, and their contexts in detail. As UCD engages the designer in all design stages, it is the most extensive engineering inquiry. Hence, all cells of the honeycomb are highlighted in Figure 2a.

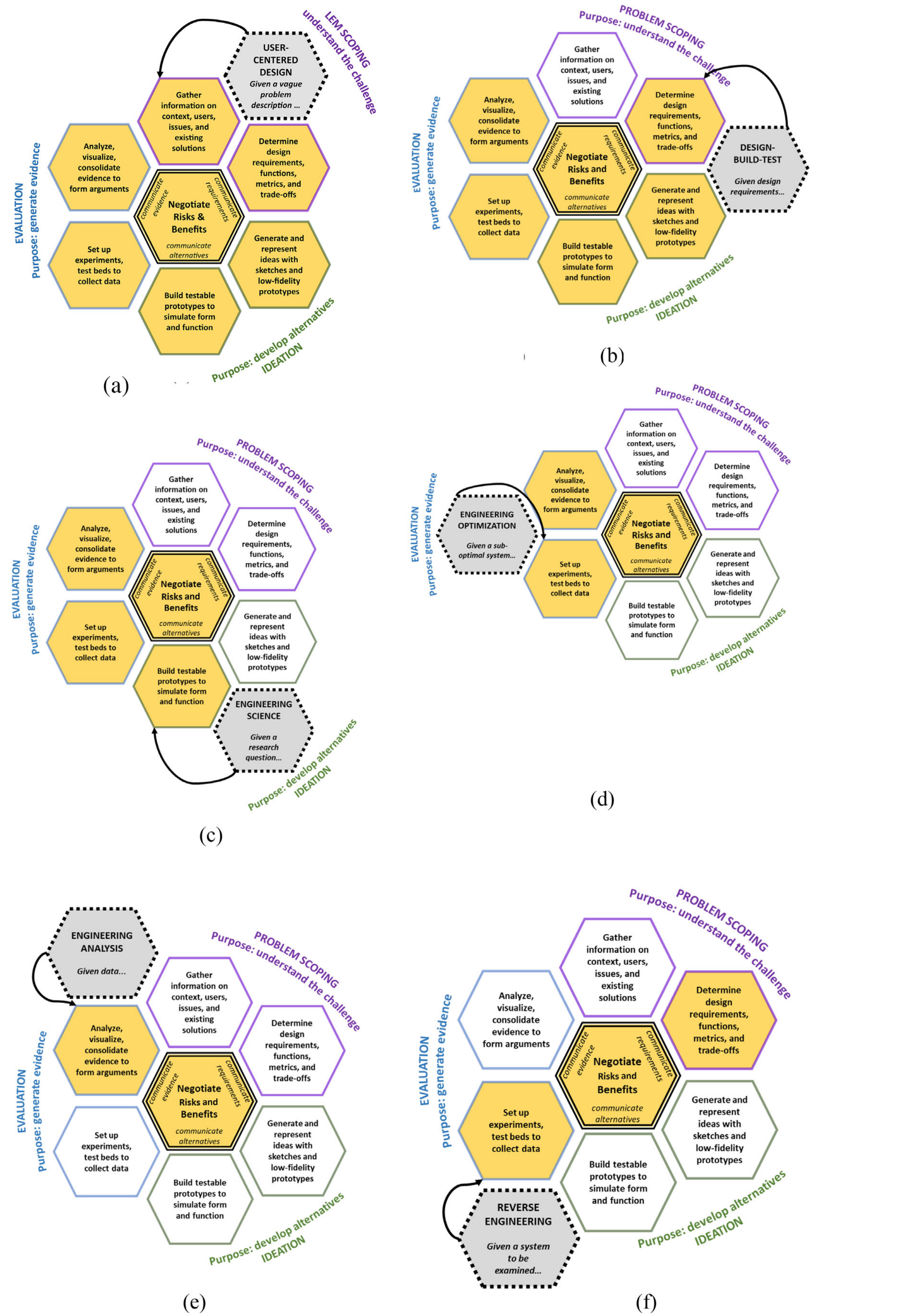

FIGURE 2 Six engineering inquiries of the honeycomb framework. Yellow cells indicate highlighted/emphasized cells; white cells indicate muted/de-emphasized cells. (a) user-centered design (UCD), (b) design-build-test (DBT), (c) engineering science (ENS), (d) engineering optimization (OPT), (e) engineering analysis (EAN), and (f) reverse engineering (REV) [Color figure can be viewed at wileyonlinelibrary.com]

5.3.2 | Engineering inquiry number 2: DBT

DBT is a hands-on approach in which prototypes are actively developed, built, and tested to establish proof of a principle, such as a failure point, or to evaluate their performance (Dieter & Schmidt, 2009). DBT focuses on applying and validating design concepts with clear goals. These projects engage the designer in all stages of the design process except for gathering information about the users because they involve clearly stated design requirements (design constraints and criteria) and solutions. As such, six of the seven cells are highlighted in Figure 2b. Rather than gathering information, as is the case for UCD, the initial step of DBT is to review a given design challenge and its set of requirements. Given a clear set of design constraints and criteria, the designer determines the metrics for success and starts generating alternative solutions.

5.3.3 | Engineering inquiry number 3: ENS

ENS is research in the context of designed systems as opposed to natural systems, leading to the generation of new technological knowledge through controlled experiments and the manipulation of variables. It provides insights concerning a specific design parameter as opposed to a complete set of design parameters (Lumsdaine et al., 2013). Engineers contribute to a body of technological knowledge, similar to how scientists contribute to scientific knowledge. The purpose of ENS is the construction of knowledge with a strong scientific research influence. The ENS process starts with a research question related to a designed artifact or system. Then, a prototype is built according to a protocol, manipulating one variable in a controlled environment to differentiate between control and experimental specimens (e.g., Jia et al., 1999). The highlighted sections of the honeycomb shown in Figure 2c emphasize building testable prototypes, setting up experimentation, and data collection and analysis, all connected by communication.

5.3.4 | Engineering inquiry number 4: OPT

OPT is broadly defined as the process of determining the best design or optimal solution based on specified design metrics, with a more specialized definition focusing on improving the performance of an existing system exhibiting a suboptimal performance (Dandy et al., 2017; Parkinson et al., 2013). The honeycomb framework employs the more specialized definition of improving the performance of suboptimal systems. In the process of optimizing such a system, engineers are required to reconcile design criteria and recognize the trade-offs necessary to improve designs (Dandy et al., 2017; Parkinson et al., 2013). The focus is on a mathematically driven approach to optimization, which aims to examine the performance of a system based on a few criteria, such as effectiveness and cost (Zwart & Vries, 2016). In such optimization, the design criteria and parameters are known and clear. As shown in Figure 2d, the process of optimization begins with a suboptimal but working system that needs to be improved. Hence, the highlighted cells involve setting testbeds and experiments to evaluate the performance of the existing system.

5.3.5 | Engineering inquiry number 5: EAN

EAN involves decision-making based on given data and alternative solutions. This inquiry places importance on mathematical computation and modeling through data analysis, and the decisions are made solely based on these calculations and mathematical models without using physical prototyping. The EAN utilizes mathematical models to inform decisions and predictions through empirical data and theoretically and scientifically known relationships. For example, in the context of mechanics or materials, EAN helps determine what is an allowable load on a structure (stresses, strains, and deformations) in response to differing conditions (Gere, 2006). In the context of life-cycle assessment in environmental engineering, this analysis may examine material flow based on conservation of mass principles at different life-cycle stages of a product such as manufacturing or transportation (Striebing et al., 2014). EAN is common in the management of manufacturing systems and engineering consulting practices. For example, when a client requests an evaluation of alternative paths, an engineer may develop mathematical models to make predictions and comparisons by analyzing a set of available data and examining a clear set of questions about a decision. Emphasis is, thus, on two cells of the honeycomb: data analysis and visualization and negotiation of trade-offs. Negotiation of risks and benefits is justified with data and other sources of evidence, including published research literature and technical reports (see Figure 2e).

5.3.6 | Engineering inquiry number 6: REV

REV is an approach that focuses on understanding an existing system or artifact by learning from, redesigning, modernizing, or fixing it (Chikofsky & Cross, 1990; Crismond & Adams, 2012; Otto & Wood, 1998). In cases of obsolete products that are no longer manufactured or maintained, REV allows renovation and redesign (Helle & Lemu, 2021). In other cases, such as in civil engineering, bridge and building designs are based on past successes to minimize the risk of catastrophic failure. In addition, when two existing systems need to interface in an application, REV helps ensure they can operate together. REV is also used for inspiration, personalization, and idea generation (Wang et al., 2021) and sometimes to ensure commercial advantage. Its methods and processes highlight two stages in the engineering design process: setting up experiments and determining design requirements, connected through communication (see Figure 2f). When a physical object needs to be created virtually using 3D scanners or computer-aided design software to support REV efforts, the cell representing building testable prototypes is also highlighted.

6 | SECTION II: PEDAGOGICAL TRANSLATIONS OF THE HONEYCOMB OF ENGINEERING FRAMEWORK

In developing the honeycomb of engineering framework, we took particular care in distinguishing the epistemological and pedagogical definitions, purposes, and arguments. We established the epistemological definitions and laid out six inquiries commonly used in engineering in the earlier sections. In this section, we outline the pedagogical translations of the honeycomb of engineering framework, which can then be effectively used to categorize existing lesson plans and guide epistemological features when developing new ones. Table 1 presents brief epistemological definitions followed by their pedagogical translation, as well as curricular exemplars.

There are two important attributes of the pedagogical translation of the honeycomb framework that we must clarify. First, when using the framework to compare lessons, it is important to remember that the framework is descriptive, not prescriptive that is, the honeycomb framework can guide lesson design but does not prescribe effective teaching. There might be effective and ineffective ways of teaching different types of engineering projects that we are not advocating here, but we argue that any judgment of quality should be made based on each of the engineering inquiries. Second, the honeycomb framework also does not call for explicitly teaching the nature of engineering as a learning objective. However, it offers a lens that can be used to view STEM education from the disciplinary perspective of engineering. This framework aims to introduce a multifaceted nature of engineering and empower educators when selecting what best aligns with their educational goals, pedagogical preparation, and resources.

6.1 | Pedagogical translation of UCD

When learning about UCD, students are typically introduced to an actual or simulated client and presented with a context-rich problem. The first task engages students in problem scoping as they gather information on users and their contexts. This exploration leads to identifying design requirements (criteria and constraints), which have not been explicitly provided to the students. Such efforts to understand the client and context provide an opportunity to make connections to scientific concepts. For example, a lesson by Sheerer and Schnittka (2012) engaged students in a context involving penguin habitats. Background information was necessary for the students to discover key design criteria on the ambient temperature at which penguins feel most comfortable.

In another example, Karahan et al. (2014) introduced students to a real-world problem impacting pelican nests in farmlands published in a local newspaper. This rich context demonstrated the need to understand and scope a problem before generating solutions. Students learned about pelicans, including their physical features and their impact on farmlands in Minnesota. In addition, Cook et al. (2015) asked students to design a prosthetic arm for a student who was born without a hand. Students gathered contextual and user information as they clarified design requirements (criteria and constraints) through problem scoping. UCD lessons can also involve a simulated or hypothetical client profile as opposed to a real one. In a lesson developed by Capobianco et al. (2013), educators used client cards representing different profiles, which prompted students to design ultraviolet glasses according to the needs of a specific client.

TABLE 1 Pedagogical translations of the honeycomb of engineering framework

Epistemological definition	Pedagogical translation of the epistemological definition	Curricular exemplars
User-centered design (UCD) enables problem solving and innovation by prioritizing the users' needs and other stakeholder wants within a context or specific situation. The design constraints and criteria are determined through problem scoping *Example*: Ford Automotive third-age suit and pregnancy suit designed to accommodate the needs of specific users	• Students are introduced to real or simulated clients or contexts • Design criteria can be articulated by clients or constructed from the exploration and understanding of users and their contexts • Students are engaged in situations rich in detail • There is a potential for real use of designed solutions in an actual context	*Elementary school*: Dolenc et al. (2016) *Middle school*: Goldstein et al. (2017) *High school*: Ilseman and Hoffmann (2016)
Design-build-test (DBT) aims to test a prototype to establish proof of a principle or to evaluate the performance of a prototype based on clearly stated design requirements (design constraints and criteria) *Example*: Building and testing airplane wings to confirm calculations of their fracture points and stresses	• The problem may include a contextual prompt but does not require a detailed examination of the user nor the context • Students are provided with clear criteria and constraints to be met • Design constraints are typically related to the materials used for prototyping	*Elementary school*: Lottero-Perdue et al. (2015) *Middle school*: Berge et al. (2014) *High school*: Bruxvoort and Jadrich (2003)
Engineering science (ENS) is conducting research in the context of designed systems (as opposed to natural systems). It leads to the generation of new technological knowledge through controlled experiments and the manipulation of variables *Example*: An engineering research project that examines the interaction between weld speed and voltage in a welding process. The engineer designs a set of experiments to identify conditions for weld strength	• Prototypes are built following a protocol, in which one variable is manipulated • Students are engaged in systematic and controlled experimentation • Students examine how manipulating one variable impacts the performance related to a specified design criterion or metric	*Elementary school*: None *Middle school*: Vassiliev et al. (2013) *High school*: Vandermeer (2010)
Engineering optimization (OPT) is the process of understanding and improving the performance of an existing system with suboptimal performance. This process requires data collection and analysis *Example*: Determining the least amount of material needed to manufacture a coil compression spring with the desired elasticity	• Scope is reduced to two or three completing criteria to allow calculations and comparative analysis • Starts by introducing a suboptimal system that requires improvement • Students are intentionally engaged in the analysis and diagnosis of factors that influence the system's performance	*Elementary school*: None *Middle school*: Dasgupta et al. (2017) *High school*: None
Engineering analysis (EAN) uses data to inform decisions related to designed systems. Engineering analysis involves the use of data analysis and mathematical modeling to make comparisons and predictions *Example*: Determining the environmental and economic impacts of installing solar panels on a building roof	• Students do not build prototypes • Students are given data or gather data from computer simulations or by actual observations • Students make calculations, analyze data, and/or develop mathematical models • Students make predictions or recommendations based on their data analysis	*Elementary school*: None *Middle school*: D'Alessio and Horey (2013) *High school*: Russ et al. (2015)
Reverse engineering (REV) is an approach that focuses on understanding an existing system or artifact to learn from, improve, document, or redesign it. Reverse engineering can be used to diagnose problems in a system or to support the integration of multiple systems *Example*: Siemens' convergent modeling technology used to create an existing physical part digitally in 3D to create new or integrated products	• Lesson starts with a given artifact that students are not familiar with • Students hypothesize how the artifact works and what its functions are • Students disassemble the artifact to understand the components of the artifact and how they work	*Elementary school*: None *Middle school*: Khalidi and Ramsey (2016) *High school*: None

6.2 | Pedagogical translation of DBT

DBT lessons start with a brief introduction of a need that serves as a motivational hook to interest students in the activity. Students are then provided with a clear set of criteria or goals to be met and the design constraints, which are typically related to materials and budget (Elger et al., 2000). These lessons engage students in developing alternatives, prototyping, and testing to improve performances. DBT lessons aim to apply and validate science concepts. For example, in a lesson on designing wind turbines, students explored energy transfer concepts (Chen et al., 2014).

DBT lessons are designed to be easy to implement, with clear design criteria or goals and accessible materials. Students are also typically given specific constraints related to materials and performance based on a specific metric. In one lesson, for example, students were asked to build a structure out of toothpicks that could withstand an "earthquake" simulated by shaking the structure (Maltese, 2009). This design project is preceded by a background on Earth science concepts and natural hazards. These lessons aim to promote student learning through engagement, construction, and reflection.

6.3 | Pedagogical translation of ENS

ENS lessons help students engage in systematic and controlled experimentation processes to understand the relationships between variables with respect to their impact on a designed artifact. Students manipulate specific variables to evaluate the outcomes of their design, and in most cases, these variables are preestablished by educators. In these lessons, students follow experimental protocols, manipulating only one variable in a prototype (i.e., specimen) for a controlled experiment. In a lesson developed by Ballyns et al. (2011), students engineered tissue samples using alginate. They manipulated the alginate gel composition to compare an experimental and controlled tissue prototype. As a result, they were able to explore the relationship between different alginate proportions and how they respectively influenced the strength of the prototype tissue.

In another ENS lesson, middle school students developed a durable plank made from dough and sawdust by manipulating different composites of the latter (Vassiliev et al., 2013). For this project, educators established variables by limiting the materials available to make the plank and the number of variables using a set of protocols (recipes) the students used to make prototype planks. The lessons also specified a control prototype that students could compare against their alternatives. These lessons aim to resemble the process of developing technological knowledge as students investigate the relationship of variables as they affect the performance of a designed object.

6.4 | Pedagogical translation of OPT

An OPT lesson usually starts by introducing students to a suboptimal system with the goal of improving its performance. Next, students engage in the analysis and diagnosis of this system. In these lessons, the critical variables of the system are specified, and students are expected to gather evidence informing optimization decisions. Testing and analysis, essential in optimization lessons, are conducted on an existing system, which can be manipulated for refinement and further testing. Hence, the process of optimization is not one of trial and error. To develop optimized solutions, students must engage in systematic testing and experimentation (Crismond & Adams, 2012; Vieira et al., 2016). An optimization lesson developed by Dasgupta et al. (2017) introduced middle school students to a suboptimal residential plumbing system with a challenge to optimize it. Students were asked to identify the variables that influence the system (e.g., the pipe dimensions that influence water pressure and material cost). By using a computer simulation and a physical prototype of the system, students were able to manipulate pipe diameter and length as they observed the impact of these changes on water pressure. Students were also constrained by a specific budget associated with the cost of pipes.

6.5 | Pedagogical translation of EAN

EAN lessons focus on making decisions based on data. In these lessons, students do not design or build testable prototypes. For example, in one lesson developed by D'Alessio and Horey (2013), students determined where earthquake warning sensors should be located on a given map. Using a web-based simulation, students gathered geological data from previous earthquakes (wave patterns and locations) to make predictions and select appropriate sensor locations. In another example, students determined sustainable approaches to farming practices (Russ et al., 2015). Similar to the previous lesson on earthquakes, students used a computer simulation that provided data on corn production, farm cash flow, and environmental factors such as water quality to determine the effectiveness of various crop planting options. While both of these lessons rely on computer simulations as the source of data, this information can also be presented in the form of spreadsheets. Students engage in data analysis and mathematical modeling in these lessons to make comparisons, predictions, and ultimately recommendations on designed systems.

6.6 | Pedagogical translation of REV

The goal of REV lessons is for students to learn from a system or artifact by analyzing, examining, or disassembling it. During this process, students determine the functions of the components to identify the artifact and its possible problems, as well as to gain inspiration for new ideas. For example, Khalidi and Ramsey (2016) asked students to identify how a roll-back tin can rolled back to the teacher's hand once it was thrown. Students developed drawings that hypothesized how the internal system might work, then disassembled, examined, and sketched the can's internal system to further identify elements that would aid their goal. In doing so, students determined the design functions necessary to simulate the can's roll-back movement.

7 | PREVALENCE OF THE SIX ENGINEERING INQUIRIES IN K–12 EDUCATION

We examined published engineering lessons to validate the efficacy of the honeycomb of engineering framework and its pedagogical translations. This examination required unbiased access to a body of curricula that are classroom-tested, peer-reviewed, credible, and not reliant on the authors' networks. The practitioner articles published in the US National Science Teachers Association's (NSTA) three journals met these criteria. Among these journals, *Science & Children* publishes curricular examples for elementary teachers; *Science Scope* focuses on the middle-school level, and *The Science Teacher* publishes curricular examples for high school teachers. These practitioner journals provided access to a variety of quality curricular examples, many of which were coauthored in collaboration with university scholars and school teachers and involved projects funded by agencies such as the National Science Foundation.

We screened all articles published between 2005 and 2019 to capture those published before and after the Next Generation Science Standards (NGSS Lead States, 2013) when engineering was broadly introduced to the K–12 education system in the United States. A total of 134 articles that made explicit connections to engineering, included sufficient details on design challenges and engineering problems, and were labeled as engineering lessons (see Figure 3). Table 2 presents the frequency of these categories across three grade-level bands. Of the 134 articles, 63 (47%) were

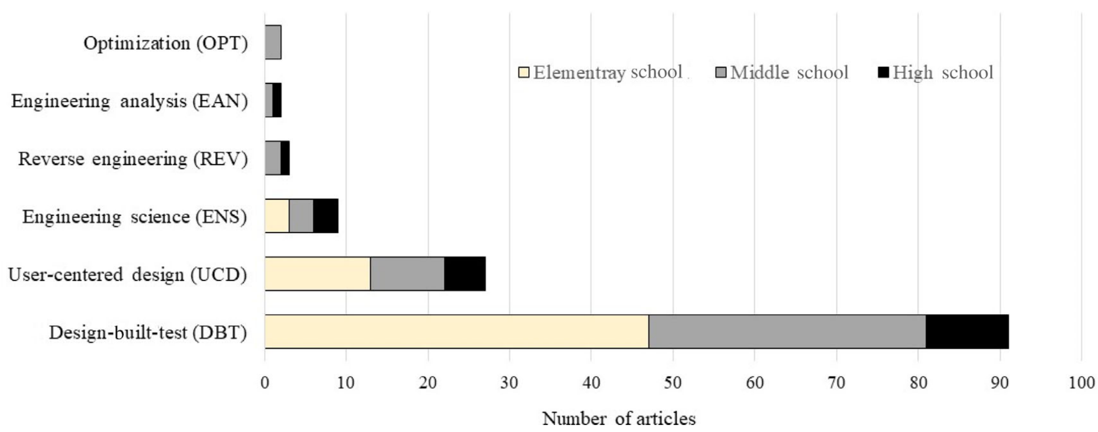

FIGURE 3 The representation of the six engineering inquiries at three grade-level bands published in the three NSTA journals between 2005 and 2019 [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 The distribution of the number of articles by engineering inquiry and grade level band

	Elementary school (*Science & Children*)	Middle school (*Science Scope*)	High school (*The Science Teacher*)
Optimization (OPT)	–	2	–
Engineering analysis (EAN)	–	1	1
Reverse engineering (REV)	–	2	1
Engineering science (ENS)	3	3	3
User-centered design (UCD)	13	9	5
Design-build-test (DBT)	47	34	10
Total	63	51	20

published at the elementary level in *Science & Children*, 51 (38%) in *Science Scope* representing the middle school, and 20 (15%) in *The Science Teacher* at the high school level.

Our examination of the published curricula illustrated that all dimensions of the framework were reflected in K–12 engineering lessons, although with varying prevalence. The DBT model was observed across all grade levels. These types of lessons and design projects were most popular at the elementary level, featured in 75% (47 of 63) of engineering lessons published at this grade level band, followed by 67% (34 of 51) at the middle-school level and 50% (10 of 20) at the high school level. In the DBT engineering lessons, students were presented with a design challenge with precise design requirements and asked to develop and test prototypes. Examples included designing a water filter that produces safe and clear water (Berge et al., 2014) and designing an ecoscape for a local park to support high biodiversity (Seymoure et al., 2013). In these projects, students typically worked with constraints associated with time and materials.

UCD lessons comprised 20% (27 of 134) of the corpus of lessons. More specifically, the UCD lessons and design projects were most frequently found at the high school level with 25% (5 of 20) of the engineering lessons published at this grade level, although a larger number of lessons were published at the elementary level with a 21% (13 of 63) representation, followed by 18% (9 of 51) at the middle-school level. These UCD projects addressed realistic needs or problems involving real or simulated clients. Students often had the opportunity to interact with experts or potential users and gather information about problem contexts. While some clients or users were fictional or abstract, the context of the problem provided to the students was often real (Ewalt et al., 2015; Karahan et al., 2014).

The nine lessons identified as ENS among the 134 articles were equally distributed across the three grade-level bands. More specifically, at the high-school level, 15% (3 of 20) of engineering lessons published at this grade level band included ENS, followed by 6% (3 of 51) at the middle-school level and 5% (3 of 63) at the elementary level. In these lessons, students typically followed a clear scripted procedure to build a prototype for testing. Students manipulated one or two variables to answer a set of research questions and make claims on various factors impacting the performance of designed objects, including material combustion (Schumack et al., 2010), nanofiber features (Vandermeer, 2010), or projects that evaluated sound intensity (Hike & Beck-Winchatz., 2015).

Only three lessons were identified as REV, two of which were published at the middle-school level and one at the high school level, and only two as EAN lessons, one each at the middle- and high-school levels. The analysis also resulted in only two lessons on OPT, and both were published at the middle-school level. In general, while most engineering lessons were published for the elementary level, they were dominated by only a few engineering inquiries, specifically DBT, UCD, and ENS. *Science Scope*, which publishes lessons designed for middle-school education, included the largest variety of lessons, exemplifying the most comprehensive representation of engineering.

As the honeycomb framework focuses on the categorization of lessons that fit a multifaceted epistemological definition of engineering, it is crucial to clarify cases where a lesson did not fit this definition. As we examined the corpus of lessons published in the three NSTA journals, many were excluded from our analysis as their design features were not specifically engineering-related. Such cases were labeled as "not engineering," even when there were references to engineering design or STEM in the text, as they did not align with the nature of engineering described earlier. Examples of such lessons include the following:

- Scientific modeling lessons. These include lessons that focused on building a physical model to apply or represent a scientific phenomenon. For example, Mcgough and Nyberg (2013) explored life science concepts by asking students to engineer a model of a plant. Students built physical models and used these models to communicate their understanding of the structure and function of plants.

- Technology-infused art lessons. These include lessons that involved design and building but did not aim to address a design need, problem, or research question. An example is a lesson by Grinnell and Sharon (2016) that asked students to design sculptures integrated with circuits, including lightbulbs.

8 | DISCUSSION

The honeycomb of engineering framework aims to delineate variations in engineering education based on an epistemological explanation. While scholars recognize the enormous breadth of engineering (Kant & Kerr, 2019), the detailed articulation of projects that engineers engage in is limited. One exception is Zwart and Vries (2016) classification of innovative engineering projects, determined based on how they differ in goals and methods, resulting in categories such as designed artifacts, ENS, and OPT. The honeycomb of engineering framework describes the breadth of engineering in further detail recognizing six ontological categorizations: (1) UCD, (2) DBT, (3) ENS, (4) OPT, (5) EAN, and (6) REV. These categories represent six epistemologically justified inquiries of engineering connected through a design process that is iterative, flexible, and adaptable.

Furthermore, the honeycomb framework goes beyond and builds on the demarcations of engineering inquiries while explicitly calling out the epistemological stances distinctly from the pedagogical stances of engineering. We do so because, in prior educational reform efforts, the treatment of "scientific inquiry" as both a disciplinary and pedagogical practice created confusion, resulting in concerns for an abundance of lessons distanced from authentic science (Chinn & Malhotra, 2002). The review of published articles of NSTA's three practitioner journals provided a pragmatic validity of the framework's utility in elementary and secondary education. Simply put, a key contribution of this paper is delineating the multiple facets of engineering and its implications for engineering education. We invite educators and administrators to consult the honeycomb framework when developing or selecting a curriculum and make upfront decisions on the type of inquiries they want to be represented in their lessons. We also recommend that teachers be introduced to the epistemologies of engineering and the relationship between epistemology and pedagogy to avoid misconceptualizations. Wendell et al. (2019) found that teachers' epistemological expectations for teaching engineering influenced the ways they taught it. The teachers in Wendell and colleagues' study adopted different ways of teaching engineering based on their understanding of the discipline, despite similar backgrounds and professional development experiences. Given that engineering is multifaceted and studies point to educators decoding engineering components differently in their classrooms (Carberry, 2014; Judson et al., 2016), the honeycomb framework is a significant contribution to teacher education. The definitions and examples provided in Table 1 provide direction for making informed decisions on the type of inquiries teachers and administrators could embrace in their classrooms and schools.

The discrepancies in the analysis of published engineering lessons, with a heavy emphasis on DBT, invite the question as to why this engineering inquiry is so prominent in precollege education. Moreover, it is interesting that ENS lessons, which more closely resemble the scientific inquiry process (a familiar model for teachers), were so few. We speculate that these patterns might be due to the prevailing narrow epistemological definitions of engineering. It is also possible that some inquiries may lend themselves to more accessible and motivating pedagogies. Especially at the elementary level, DBT lessons may be widely used due to their potential to generate enthusiasm and engagement among students. Our analysis of NSTA's articles also showed that engineering practices with heavier data components, such as OPT and EAN, were underutilized. According to Peters-Burton and Johnson (2018), modeling and analysis were also among the least prominent topics covered in the STEM-focused high schools they examined. Increased attention to these two inquiries of engineering (OPT and EAN) could help address the difficulties of integrating mathematics with science and engineering, especially at the high school level (Becker & Park, 2011; English, 2016). Curriculum developers should build on existing lessons, develop OPT and EAN lessons, and examine how these lessons promote performance objectives in mathematics.

The honeycomb of engineering framework promotes research in engineering education by enabling researchers to categorize curricula and compare the efficacy of different engineering inquiries on student learning and engagement. Future research needs to evaluate if an emphasis on different engineering inquiries would result in different learning outcomes. Some emerging research supports this conjecture. In one study, after comparing a user-centered model with a DBT model, the UCD model was found to facilitate learning related to solar energy concepts, while the DBT model promoted understanding of trade-offs (Goldstein et al., 2018).

Finally, a further examination of the philosophy of engineering is needed. According to Bucciarelli (2003), engineering and philosophy may appear worlds apart, yet research on the epistemology of engineering is essential to guiding engineering education. The honeycomb of engineering framework is one step in that direction with its epistemological foundation, highlighting the field's multifaceted and multidisciplinary nature. As illustrated in this conceptual article, a philosophical perspective provides a conceptual clarification and a better articulation of the epistemic practices of engineering, resulting in a framework that helps explain current practices and compare existing curricular efforts.

As we promote wide dissemination of the honeycomb framework, we want to make several distinctions clear to avoid misuse due to misinterpretation. First, we do not recommend the use of all inquiries or suggest that certain inquiries are more important than others. Our intent is that the honeycomb framework provides a nuanced view of engineering and a nuanced set of options for pedagogy. Second, the hexagonal cells of the honeycomb framework should not be confused, based on resemblance, with the Stanford d.school's (2021) design process model promoting innovation culture and methods through empathy and UCD. The honeycomb framework embraces the human-centered perspective of design innovation under the UCD inquiry. However, it specifies five additional ways engineering adds value to society. The framework also positions negotiation at the center of the honeycomb to facilitate iteration and avoid the impression of a sequential flow.

A limitation of the study is that the lesson analysis was conducted on a sample of lessons published in the United States, challenging the framework's generalizability. Future research in other contexts and regions is needed. Countries with a long history of intentional integration of engineering and technology in K–12 education, as well as those with emerging developments, need to be examined. Additional critiques of the honeycomb framework could be that it does not make explicit the interdisciplinary connections to science, mathematics, and other disciplines nor such mindsets as the engineering habits of mind and ethics. These questions are all important. Within a research landscape with few examples that connect engineering philosophy and engineering pedagogy, we envision that the honeycomb of engineering framework will inspire many more questions, be a trailblazer for new research paths, and inspire a renewed vision for practice in engineering education.

9 | CONCLUSION

This conceptual paper describes the honeycomb of engineering framework, which is an ontological classification of multiple facets of engineering mapped to the core practices of design. The framework conceptualizes engineering as creating, monitoring, managing, and improving technological systems through the purposeful negotiation of risks and benefits. Most notably, we caution educators and researchers against a monolithic definition of engineering. Developed based on an engineering philosophy, the honeycomb of engineering framework helps distinguish the pedagogical motives from the philosophical underpinning of the engineering discipline. Without such a distinction, there would be a disarray of terms and concepts, misinterpretations of epistemic practices, and confusion about pedagogical purposes. While the pedagogical translations of the framework are undertaken for precollege education, the framework promises to guide engineering education efforts at all levels. The framework both calls for and guides future research and teaching in engineering education, as well as further prospects for the philosophy of engineering guiding engineering education.

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