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Characterizing engineering work in a changing world: Synthesis of a typology for engineering students' occupational outcomes

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Abstract

Background: Engineering education research frequently examines students' persistence (or intentions to persist) into engineering careers from engineering school. However, the variety of engineering-related occupations has increased substantially in recent years, challenging researchers' abilities to discern what constitutes persistence in engineering.

Purpose: This article investigates the question: How can researchers categorize students' occupational outcomes in terms of engineering relatedness in a manner that enables consistency across future studies and that is informed by enduring conceptions of engineering work? We develop an occupational outcomes typology in response to this question.

Scope/Method: We employed systematic literature reviews to substantiate the typology. In total, we reviewed 259 sources published between 1966 and 2016. Review 1 examined sources discussing or debating the presence of unifying occupational attributes across engineering practice. Review 2 examined sources discussing common job functions constituting unifying criteria identified in Review 1. Review 3 examined sources discussing specific work activities associated with functions identified in Review 2. Finally, Review 4 examined job profile data from the year 2017 on 1100 job titles to identify contemporary nonengineering-titled jobs involving activities similar to activities found in Review 3.

Conclusions: Engineering practitioners' possession of design responsibility—their responsibility for products' efficacy and safety through governance of designs (new or existing)—has served as a unifying work attribute over time. We find that the 21st century has given rise to interrelated roles encompassing and surrounding conventional engineering work and propose a typology that categorizes occupations in relation to engineering. The typology offers a responsibility-based framing of engineering that helps educators illustrate key distinctions among contemporary engineering-related occupations.

KEYWORDS
careers, diversity, persistence, systematic review

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1 | INTRODUCTION

The 21st century has brought an expansion in the variety of occupational roles associated with product, service, and technology development (Downey, 2005; National Academy of Engineering [NAE], 2018; Stevens et al., 2015; Williams, 2002). As a result, it has become more challenging to classify the types of occupations engineering students undertake in their careers. This article introduces a typology to facilitate consistency among researchers who measure occupational outcome as a dependent variable in original research on engineering students' career trajectories such as in studies of underrepresented groups' persistence in engineering. We synthesize the typology from the results of a series of systematic literature reviews that examine which work attribute(s) have been discussed as evidencing unity in engineering practice over time. Based on these reviews, we derive a set of propositions that distinguish types of occupational outcomes: conventionally recognized engineering work, engineering-coupled work, and other work—the latter of which can be further decomposed into other work that employs engineering domain knowledge or skills and other work that does not. These propositions underpin the typology's categorization scheme for occupations' engineering relatedness. Furthermore, we discuss how this scheme can enhance transparency and comparability across studies that examine engineering occupational participation, contributing toward a recent call from the NAE (United States) to "establish a better empirical foundation" for research on engineering career paths (NAE, 2018, p. 123).

By developing a typology based on fundamental work attributes rather than job titles, it is our hope that this study can provide researchers with a reliable reference frame as job titles, role formulations, or entire technology areas continue to come and go. Similarly, in service to educators in these dynamic times, this typology offers a responsibility-based framing of engineering work that can help introduce students to key differences across the range of distinct yet seemingly similar career options they now face.

1.1 | Engineering work: The case for a unifying framework

As today's educators strive to align student aspirations with careers in engineering, we notice a concurrent call to clarify what working as an engineer really means in the 21st century (Mote, 2014, 2015; Vest, 2011). Assessing this alignment is challenging without a reliable way of ascertaining what students do upon entering the workforce. Engineering educators working to ensure students' career preparedness and to strengthen diversity in engineering fields require a feedback loop that informs about students' occupational outcomes.

Yet measuring these occupational outcomes and their congruence with familiar engineering roles has become increasingly difficult. The turn of the 21st century has ushered a "rise of the project workforce" (Melik, 2007) marked by a substantial broadening of the range of project and product analytical, coordinative, and strategic roles within technology-related industries (e.g., Hodgson et al., 2011; Hong et al., 2005; Rauniar et al., 2008; Salzman & Lynn, 2010; Van de Weerd et al., 2006). These often cross-disciplinary jobs blur traditional boundaries of engineering work and strain our existing ability to measure engineering occupational participation. Existing measurement systems have ranged from nations' labor statistics programs (e.g., Australian Bureau of Statistics, 2019; US Bureau of Labor Statistics [US BLS], 2018a; UK Office for National Statistics, 2018) to educational research agencies' occupational outcomes tracking programs (e.g., Higher Education Statistics Agency [UK], 2018; US National Science Foundation [US NSF], 2019) to individual universities' alumni surveys.

Changes in the occupational landscape have compounded society's already tenuous understanding of engineering work in our present time, prompting leaders in engineering education to call for renewed clarification. In the United States, for instance, former NAE president Charles Vest (2011) concluded: "engineering as a profession has done a poor job of communicating what engineers really do" (p. 8). A branding expert called on by the NAE to study the matter characterized engineering work as "decentralized," adding that: "engineers themselves do not always agree on what engineering is" (Baranowski, 2011, p. 15). Current NAE president C. Dan Mote (2015) recently listed strengthening public understanding of engineering among the top strategic goals of the Academy.

While this "decentralization" is on the one hand a testament to the reach engineering has had across industries and organizations, it has made engineering graduates' career paths difficult to interpret. Historians and educators have been forthright in asserting that "engineering is undergoing … [an] expansive disintegration" (Williams, 2002, p. 30) and that engineers suffer "invisibility" among an increasingly complex array of occupational roles (Newberry, 2009). A recent report from the NAE, meanwhile, finds that 45% of engineering graduates in the United States undertake occupational roles characterized as "engineering proximate"—jobs that defy conventional categorization in engineering yet leverage engineering-related knowledge and skills. In one of its primary recommendations, this report cites a need to "establish a better empirical foundation" for research on engineering career paths (p. 123), and it presents findings on engineering workforce participation using varied criteria (e.g., individuals' job classification by standard governmental job code, the type of knowledge and skills individuals use at work, or the type of degree individuals have earned) to ensure interpretability and clarity (NAE, 2018).

Our study contributes to improving this empirical foundation by advancing the development of a shared conceptualization of occupations' engineering relatedness. We first inquire about the presence of enduring core identifier(s) of engineering work through a search for occupational attributes that have been discussed as evidencing unity in engineering practice over time. We then investigate how these core elements of engineering work nest within the network of related roles in today's product, service, and technology development workforces. These findings allow for synthesis of an objective and a communicable framework for assessing occupations' engineering relatedness. We are cautiously aware of categorization challenges posed by engineering's continued evolution; Williams (2002), for instance, warns that engineering's expansion away from a well-defined profession and toward a "hybrid" occupation make attempts at bounding engineering futile given "dynamic[ism] at [engineering's] peripheries, where it is most engaged with science and with the marketplace" (p. 80). Consequently, this study seeks not to bound the extremities of engineering; it instead inquires about a basic enduring center to engineering work while allowing for the continued outgrowth of contemporary occupations.

Furthermore, we pursue to the extent possible a categorization scheme that embraces students' wide-ranging job choices and avoids negative labeling yet provides an objective means for data standardization for engineering education research. We presume educators are concerned with whether students' participation in engineering careers is waxing or waning and whether this participation varies across demographic groups. Many reports, for instance, point to women's continued underrepresentation in engineering occupations (e.g., Ayre et al., 2013; US Census Bureau, 2014; Hunt, 2016; NAE, 2018); yet the growth of "engineering-proximate" occupations (NAE, 2018) suggests that conventional binary occupational categorization (e.g., "engineering" vs. "non-engineering") may hinder researchers' ability to be consistent in how they measure and report women's (and all individuals') participation in engineering work. Assessment of occupational participation trends requires a means for consistent measurement, which in turn would better enable meta-analyses of future published engineering education research on students' occupational outcomes. To the extent there exists a core occupational characterization of engineering, a shared typology can help researchers establish whether students (as a whole or as demographic subsets) are gravitating toward or away from it.

Constructing the typology, however, first requires understanding and accounting for the historic and pragmatic reasons why it has become so challenging to consistently identify engineering jobs. We review these considerations before presenting goals and methods for typology development.

1.2 | A history of identification challenges

Our present period is by no means the first characterized by a struggle to identify the bounds of engineering practice. Scholars have observed engineers grappling with how to define their field throughout its complex history (Downey & Lucena, 2004), which has spanned from the modest beginnings of a craft occupation (Seely, 2005) through the rise of formal engineering professional societies in the 19th century (Grayson, 1980; Layton, 1971) through the onset of global practice sharing near the turn of the 20th century (Dreicer, 1995; Grayson, 1980) through a reformulation of engineering education around an "engineering science core" in the early to mid-20th century as European approaches intersected with American curricula (Grayson, 1980; Seely, 1999, 2005) to the more recent rise of high tech, the internet, and globalization. When practitioners first banded together to form engineering professional societies, they set out to establish systems of credentialed privilege and to standardize arcane knowledge—efforts that marked the first serious attempts toward forging professional unity in engineering practice (Grayson, 1980; Layton, 1971; Meiksins, 1988). Yet beyond their direct intended benefits to practitioners, these efforts at professional standardization and boundary setting were also spurred by serious safety, quality, and ethical concerns associated with rapid technological evolution and its strain on public trust. The American Society of Mechanical Engineers (ASME), for example, traces its coming of age to the aftermath of a major boiler explosion (ASME, 2019).

Historians describe a push toward professional unification in the late 19th and early 20th centuries. In the United States, for instance, this movement peaked during a period Layton (1971) called "the revolt of the engineers" in reference to the years surrounding World War I—a high point of solidarity among practitioners after which dispersion and decentralization of engineering practice generally prevailed (Layton, 1971; Meiksins, 1988; Seely, 1995). As Seely (1995) explains, "engineers … had been determined to achieve the recognition, prestige, and professional status that society accorded to law, medicine, and other professions" (p. 742). Yet evidence points toward corporatization of engineering careers as a key factor in the movement's eventual dissolution: Many practitioners became satisfied with prospects of promotion from engineering roles into the managerial and executive ranks of companies (Layton, 1971; Meiksins, 1988). As this wave of activism dissipated, one can argue that engineers achieved a path to the career prestige they sought—it so happened to blur the professional bounds of engineering.

As World War II gave way to the Cold War, engineering practitioners again pursued professional unification and recognition, a movement some historians see as responsive to the credit granted to scientists for wartime accomplishments (Seely, 1995). Kemper (1967) summarizes a motivating perspective: "Every rocket firing that is successful is hailed as a scientific achievement; every one that isn't is regarded as an engineering failure" (p. 84). The "physics envy" (Seely, 1995, p. 747) that followed the Second World War corresponded with the engineering community's shift to endorse engineering science as the backbone of engineering education (Grayson, 1980; Seely, 1999, 2005). Here, curricular reforms proportionally increased science among required content—a move that some thought would prove legitimizing for the profession yet one that may have served to weaken the links between practitioners and the educational system (Seely, 2005).

A less-unified practitioner base eventually paralleled an expansion in scope and variety of engineering work itself, which proceeded to evolve throughout the remainder of the 20th century (Downey, 2005; Williams, 2002). On the one hand, the public began to confuse scientists and engineers (Bush, 1965; Petroski, 2010) while on the other previously unforeseen engineering–marketing and engineering–business hybrid roles emerged as well as roles uniquely tuned to computing and software realms (Rauniar et al., 2008; Van de Weerd et al., 2006; Van der Linden et al., 2007). Some may consider this evolutionary flexibility a boon to contemporary product development activity; others may feel unease about dilution of engineers' conventionally ascribed professional duties (Busby & Coeckelbergh, 2003). Either way, we have witnessed the bounds of engineering practice stretched in at least two dimensions: first, in the diversity of capabilities called upon across varied roles (Downey, 2005; Williams, 2002) and second, in practitioners' career progressions tending toward roles with increased managerial components (Biddle & Roberts, 1994; Busby & Coeckelbergh, 2003; Hodgson et al., 2011; Rynes et al., 1988). Today, we observe diverse expectations about engineering work in industry and about the breadth of roles aspiring engineers can pursue in their careers (Brunhaver et al., 2013).

Yet amid these broadening conceptions of "engineering," longstanding professional societies have endured with relatively consistent missions, professional engineering licensure remains requisite in certain areas of practice, and engineering honor societies espousing enduring values remain affixed to engineering educational and professional scenes (Seely, 2005; NAE, 2017, 2018; Watkins & Ostin, 2018). Scholars of engineering practice point out that social and coordinative tasks have long been part of the inherent "heterogeneity" of engineering work (Stevens et al., 2015, citing Law, 1987) and should be acknowledged not solely as evidence of new hybrid roles but as frequent occurrences in the core practice of engineering (Bucciarelli, 2002; Stevens et al., 2015; Trevelyan, 2007, 2010). Where some historians see evidence of disintegration, others sense an impetus to identify binding ties and to establish robust, contemporary disciplinary descriptions. Engineering educators, for example, have responded to this impetus through initiatives that affirm key competencies and refine curricula for a new era (e.g., American Society for Engineering Education, 2016; Crawley et al., 2014; NAE, 2004, 2005; Sheppard et al., 2009). We do not challenge or reinvent such valuable work; rather, we limit our scope to developing a framework for categorizing students' occupational outcomes in terms of engineering relatedness.

1.3 | Recognizing key competing perspectives

Prominent engineers and educators have previously offered no shortage of engineering occupational descriptions: "scientists study the world as it is; engineers create the world that never has been" (Von Kármán, as quoted in: US NSF, 2012); "engineers … apply science and mathematics … to build products to meet the needs of mankind" (National Society of Professional Engineers, 2006); "engineers create products and processes … to enhance … our everyday lives" (Martin & Schinzinger, 2005, p. 1). These descriptions may serve noble purposes of boosting public interest and support but offer little practical assistance in distinguishing the engineering jobs from among contemporary job listings.

More formal attempts to distill basic unifying criteria for engineering occupational roles reveal incongruence between two prominent camps in the literature. Specifically, sociologists and the scholars of engineering ethics differ in concluding whether engineering is recognizable as a distinct profession. Bailyn and Lynch (1983) summarize a sociological perspective: “engineering, even though it is based on technical expertise, [is not] a profession … practitioners have been shown, as a group, to subscribe more to [employing organizations' values] than to professional values” (p. 264). Meiksins (1988) adds: “what was missing … was any serious commitment to the idea of the engineering profession as a whole as an independent, organized force” (p. 224). Williams (2002) concludes: “Engineering has evolved into an open-ended Profession of Everything … with no strong institutions to define an overarching mission” (p. 70). This community asserts that engineering practitioners, despite commonalities in their technical knowledge and skills, relinquish control of the specifics of their work roles to the market where employers make adjustments as needed to fit operational contexts. Today, we see a perpetual outgrowth of diverse job titles and hybrid roles that challenge the concept of engineering as a distinct and cohesive occupation.

Engineering ethics texts, meanwhile, tend to reference one or more from among certain criteria in their cases for shared professional bounds in engineering practice: (1) requisite advanced skills and knowledge, (2) self-regulation (i.e., the profession controls its own standards for membership and performance), and (3) practitioners' shared embrace of duty toward public good (Fleddermann, 2004; Martin & Schinzinger, 2005; Whitbeck, 2011). As Davis (1997) discusses, social scientists tend to focus more heavily on self-regulation and membership control criteria of professional definitions compared to engineering ethicists' more predominant focus on embrace of shared duty, a conclusion aligned with the observation that some engineering ethics texts soften or leave out the self-regulation criterion (e.g., Baura, 2006; Harris et al., 2013). These differing foci of professional definitions help explain inconsistencies among scholars' conclusions about professional unity across engineering practice.

While engineering's status as a distinct profession may not be universally agreed upon, our review nonetheless suggests relatively wide support for certain indicators of occupational cohesion in engineering. This support while inconclusive by itself can help us build reasonable defining propositions about engineering occupations when coupled with a systematic review of the engineering practice literature. One such example related to the public duty professional dimension is reiterated across engineering ethicists' accounts: Those in engineering roles hold responsibility for the efficacy and safety of products (or processes, services, or systems) (e.g., Fleddermann, 2004; Harris et al., 2013; Martin & Schinzinger, 2005; Whitbeck, 2011). We call attention to this *design responsibility* concept from ethicists' analysis—which refers not specifically to the act of designing (verb form) but to engineers' stewardship over designs (noun form) be they new or sustained designs—for several reasons. First, it stands out as a factor that social scientists do not appear to refute in their accounts of engineers' roles or their critiques of engineering professional status. Second, its prevalence in the literature suggests its possible centrality in what defines engineering roles. Third, it has the potential to be connected to visible, measurable activities of engineering roles. Meanwhile, social scientists and engineering ethicists also appear to generally agree about the specialized knowledge or skill criterion of engineering roles. Social scientists, however, explicitly reject the professional self-regulation criterion: Practitioners' cession of job, career, and career path definitions to organizational or market control is a primary basis of their dispute of professional unity in engineering practice (Bailyn & Lynch, 1983; Layton, 1971; Meiksins, 1988; Williams, 2002).

It is not the goal of this article to demonstrate whether engineering is a profession; as Van de Poel (2010) discusses, a conclusive analysis here may be impossible. It is, however, our goal to identify a widely recognized center of gravity among engineering jobs so as to propose a basis for an occupational relatedness scale. To this end, our systematic review first examines published analyses and critiques of engineering's professional cohesion in order to uncover both shared and discordant occupational attributes across roles. Reviews of the engineering practice literature then allow us to identify how observable markers of the shared attributes tend to manifest in occupations in practice. Finally, we examine occupation description data to characterize the role breakdown in contemporary engineering practice, inclusive of core and related roles, in order to build the typology.

1.4 | Why refine the categorization approach? The present pragmatic challenges of categorization

Recent decades' proliferation of new job roles and titles strains the transparency and precision of existing occupational participation measurement systems. These systems are employed by many nations to characterize their workforces (e.g., Australian Bureau of Statistics, 2019; US BLS, 2018a; UK Office for National Statistics, 2018), and higher-education research agencies also rely on components of these systems to assess graduates' occupational participation (NAE, 2018, p. 17). In the American, British, and Australian examples cited above, systems attempt to account for occupational participation across all working individuals by first establishing a standardized list of occupations, periodically surveying subsets of employers or households about numbers of employees at those occupations, and then extrapolating to construct proportionally accurate national workforce cross sections. In the case of the United States, the "standard occupation classification" codes used by the BLS are updated relatively infrequently (at approximately 8-year intervals) and account for 867 occupations (US BLS, 2018b), 18 of which are designated as "engineers" (US BLS, 2018c, p. 6–7). The BLS acknowledges that the set of 867 codes is far too sparse to cover many individuals' exact jobs, particularly for those in hybrid roles; yet because of the organization's imperative to provide proportionally correct workforce descriptions, it is essential that the same individual not be counted in multiple job categories simultaneously (US BLS, 2018b). This single-counting imperative limits this type of system's ability to convey a consensus count of individuals working in near-engineering roles not titled as "engineer." As a BLS Labor Economist explains, individuals in roles related to project management, for example, might be counted once in "construction management" or "information systems management," but they cannot be simultaneously counted as "engineers" (DiVincenzo, 2006, p. 19).

While national labor statistics systems serve key purposes in tracking the relative sizes of industries and broad categories of work, their categorical imprecision can impair researchers' abilities to fully understand occupational outcomes among those in engineering pathways. The NAE (2018), for instance, notes "considerable ambiguity" (p. 17) in how labor statistics codes have been employed in reports classifying occupations undertaken by degreed engineers in the United States, particularly for computer- and management-related roles. Lowell et al. (2009) similarly discuss how categorical obfuscation likely occurs throughout workforce statistics pertaining to engineering graduates. In light of current systems' limitations, this study proposes an enhanced categorization approach tailored for engineering education research on occupational outcomes. The approach centers on assessing occupations' relation to longstanding intrinsic work attributes in engineering rather than on job titles to mitigate sensitivity to obsolescence and to accommodate a range of engineering relatedness across roles.

2 | PURPOSE AND CRITERIA FOR AN ENGINEERING STUDENTS' OCCUPATIONAL OUTCOMES TYPOLOGY

The exploration of connections between educational, social, and demographic factors and engineering students' career outcomes constitutes a vibrant research area. In engineering education, various recent studies have examined educational experiences and interventions in relation to students' occupational outcomes or aspirations (e.g., Atman et al., 2010; Dasgupta et al., 2015; Eris et al., 2010; Godwin et al., 2016; Lichtenstein et al., 2009; Lord et al., 2009). Similarly, in sociological and interdisciplinary work, researchers have examined diverse factors tied to individuals' persistence in engineering career pathways (e.g., Cech et al., 2011; Correll, 2004; Herman, 2015; Hunt, 2016; Seron et al., 2016). All such studies involve establishing what counts as engineering work, yet researchers' ability to consistently measure this variable is limited without a unified method that accommodates a wide range of occupations. In this light, the NAE (2018) suggests a need for a stratified approach to measuring what counts as engineering work given their findings of substantive percentages of graduates employing engineering-related knowledge or skills at jobs not conventionally categorized as "engineering." A multinomial engineering-relatedness framework for categorizing occupations holds promise to enrich our understanding of students' careers although it could also sustain the risk of measurement inconsistency if it relies on subjective or vague notions of the applicability of engineering knowledge or skills at jobs.

The primary objective of the study reported here centers on the question: How can researchers categorize students' occupational outcomes in terms of engineering relatedness in a manner that both enables consistency across future studies and that is informed by enduring conceptions of engineering work and profession in literature? To address this question, we employ the following criteria to guide construction of an occupational outcomes typology:

- The typology shall provide a means of consistently categorizing occupations in terms of their engineering relatedness.
- The typology's unit of analysis shall be occupations rather than individuals (i.e., it shall not attempt to designate individuals as "engineers"). Relatedly, the typology shall not be professional membership-based and shall not attempt to designate the engineering professional status of individuals or roles.
- The typology shall accommodate the possible changing nature of engineering work across career stages, encompassing entry-level roles through advanced career roles.

- The typology need not force occupations into binary categories (e.g., "engineering" vs. "non-engineering"); more than two engineering-relatedness categories may comprise the typology.
- Category labels to the extent possible shall be neutral in tone and shall not imply that any one occupation category is more important than others.

Basing the typology upon existing literature carries an inherent risk: This approach could be viewed as constraining conceptions of engineering work to those of the past. Yet for the typology to lend itself to adoption, it must be broadly recognized as valid, which in turn likely depends on some degree of compatibility with enduring stakeholder communities' (e.g., professional societies', accreditation boards', employers', etc.) ongoing operation. These concurrent considerations suggest a need for balance: a typology that is historically grounded without being historically constrained. Toward this balance, we elect to synthesize the typology from broad themes found to be recurrently present in literature spanning a wide time range. As we later discuss in *Limitations of Methods and Results*, the thematic clustering approach we employ here carries the tradeoff of limiting the comprehensiveness and precision of the resulting typology. Yet this broad approach helps to avoid synthesis of fragile categorization criteria and increases the likelihood that the typology can be further refined without introducing conceptual conflicts as new themes about engineering work emerge. The assumed need for recognized validity among existing stakeholders in sum leads us to an approach that produces a "fundamental but incomplete" basis for the typology, implying as we discuss in *Future Work* a responsibility for users of the typology to continue monitoring for prominent emergent themes in contemporary engineering practice.

Finally, we focus on constructing the typology for original research use cases, particularly studies where researchers have the opportunity to query individual respondents about details of their occupations (or aspired-to occupations). The typology can support such efforts as longitudinal studies, tests of interventions, or alumni surveys where engineering students' occupational outcome is a variable of interest.

3 | SYSTEMATIC REVIEW SEQUENCE: METHODS AND FINDINGS

We carried out a series of nested systematic literature reviews to first identify unifying attributes of engineering occupations and to subsequently examine how these attributes map to the broader set of present-day occupations. Content analysis from initial review rounds informed search terms for later rounds in a four-part sequence of inquiries: (1) in literature assessing engineering's status as a distinct profession, *what occupational attribute(s)* are most consistently discussed as evidence of unity across engineering practice? (2) *What job functions* are involved in carrying out these unifying attribute(s) of engineering occupations? (3) *What specific types of activities* compose these engineering job functions? and finally (4) *What occupations* involve similar or related activities to various extents? Findings from these inquiries enabled us to establish propositions about the engineering relatedness of occupations, which informed construction of the occupational outcomes typology (refer to *Typology Synthesis and Discussion*).

We employed best practices for systematic search, results qualification, and literature review as summarized by Petticrew and Roberts (2006) and Borrego et al. (2014, 2015) and describe our application of these methods to each search round in the section that follows. Although the search terms for the rounds differed, all adhered to similar guidelines for repeatability and reliability (Borrego et al., 2014): Construction of clear research questions and scope, definition of result inclusion criteria, identification of specific databases to search, definition of result qualification criteria, establishment of a results synthesis approach, and identification of methods' limitations.

The first three search rounds considered sources from academic journal articles and books identified through two search portals. The first was an EBSCO Host meta-search engine accessing several leading databases, including *Education Source*, *Academic Search Complete*, *Business Source Complete*, *ERIC*, *PsycARTICLES*, and e-journal sets from many publishers (for complete database source information, see EBSCO Host, 2016). A second portal, WorldCat, was utilized specifically for book searches, providing access to the catalogs of over 10,000 libraries globally (WorldCat, 2016). We did not limit the country of origin of results from either portal. Between EBSCO Host and WorldCat, we employed a deliberately broad search across disciplines such as sociology, history, education, business, and engineering given the cross-disciplinary nature of this study's topic. Search 4 on the other hand was conducted specifically within the *Occupational Information Network (O*Net)* database in order to access its extensive, consistently formatted database of detailed occupation descriptions (Hanna et al., 2019; Peterson et al., 2001). While O*Net's data draws from US employment contexts, its international reach has grown in recent years, with the platform's use for occupations-related studies, services design, or policy advisory projects spanning 36 nations (Hanna et al., 2019, p. 600–603).

After acquiring raw search results, we conducted manual qualification review and filtering based on inclusion criteria established for each search (Petticrew & Roberts, 2006). Here, we also introduced a small number of titles (i.e., fewer than 5% of any search's result count) into the results lists from among literature we were aware of that did not turn up via automated search. Any added titles fully complied with the search logic and were either over 15 years old or came from chapters within larger works, instances where incomplete source indexing or limited digitization are probable causes for the sources' failure to be retrieved automatically. For each of Searches 1–3, manual result qualification was accomplished in multiple passes through the systematically retrieved document sets. The first pass entailed within-document key word searches to verify general topic coverage. We retained any source that did not explicitly violate qualification criteria for a second-pass analysis. The second pass entailed determining contexts in which key words were used via body text review; for example, was a key word used as part of a discussion related to the specific search question, or was it used as a common noun in a discussion about something else? Sources that passed both qualification review rounds were retained for content analysis while summary lists of excluded source topics were recorded. Content analysis methods as described by Krippendorff (2004) allowed us to establish summative themes from content clusters identified among each result set; these analyses were carried out uniquely for each of Searches 1, 2, 3, and 4.

3.1 | Search-specific questions, methods, and literature review results

Figure 1 illustrates the nested and sequential literature search and review processes. We present the synthesis of results for each search round immediately following a description of its methods (e.g., its search question, means of systemization and qualification, and content analysis) beginning with Search 1.

3.1.1 | Search 1: Identifying unifying attribute(s) of engineering practice

> **Search question**: *Among literature that analyzes engineering's status as a distinct profession, what occupational attribute(s) are discussed as evidence of unity across engineering practice (or, if applicable, are discussed as evidencing dis-unity across engineering practice)?*

In Search 1, we searched a wide date range from 1966 to 2016 to trace the historic critique of professional unity in engineering. We ran five subrounds of search to span varied areas of literature in which scholars may have engaged in this critique. Aware of the differences between engineering ethicists' and social scientists' conclusions here, we designed the subrounds of Search 1 to ensure coverage, at a minimum, of literature in those areas. Each subround featured specific subject terms, text terms, and search logic as summarized in Table 1. Qualification review of the Search 1 raw results verified that sources commented on professional cohesion in engineering and discussed factors unifying

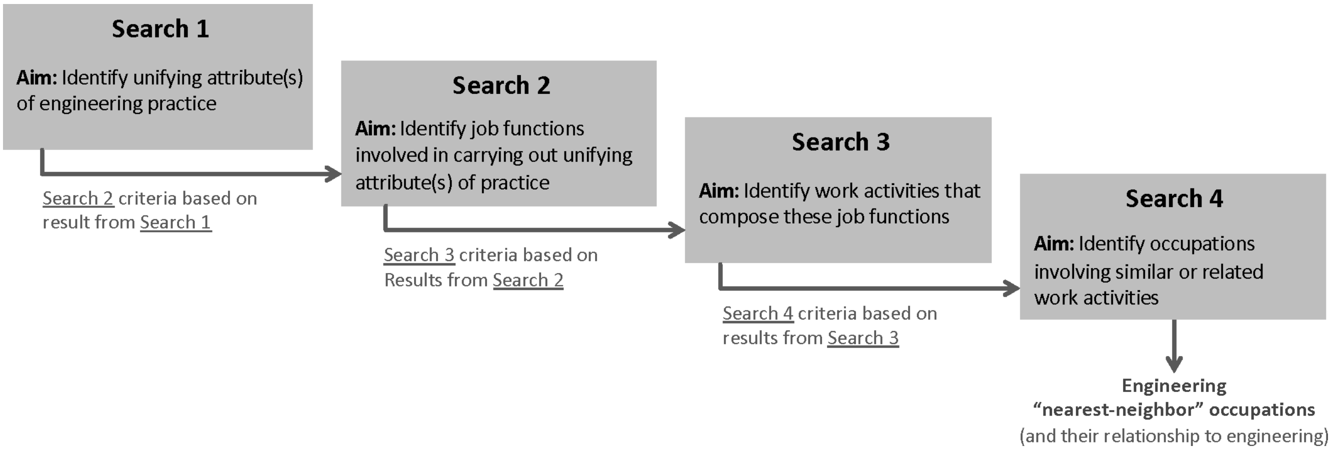

FIGURE 1 Sequence of nested searches employed in systematic literature review

TABLE 1 Search 1 criteria and results count: Sources analyzing engineering's status as a distinct profession

	Subrounds of search				
	1	**2**	**3**	**4**	**5**
Subject search terms	engineer* OR technolog*	engineer* OR technolog*	engineer* OR technolog*	engineer* OR technolog*	engineer*, ethics
Body text search terms	work, occupation, career, organization	engineer*, profession, history, change	engineer*, profession, history, ideology	engineer*, profession, history, "engineering education"	engineer*, ethics
Subject exclusion terms	← "K-12," counseling, immigration, "high school," legal, marketing, operations, parent* →				
Media	← academic journal articles and books →				
Date range	← 1966–2016 →				
Raw results counts	367	316	167	347	426
Qualification:					
Inclusion criteria	← Source must specifically comment on the professional status of engineering → ← Source must provide discussion or analysis on what unites (or strains the unification of) engineers →				
Primary topics of excluded sources	Curriculum, faculty, graduate student issues, job counseling job search, pedagogy, STEM policy, salaries, specific engineering design issues	Curriculum, early education, faculty, history of specific products or technologies, pedagogy, science-specific issues, specific engineering design issues	Early education, faculty, specific engineering design issues	Curriculum, engineers' salaries and job markets, faculty, job counseling, job search, life-long learning, offshoring, pedagogy, STEM policy, graduate student issues	Ethics in experiments, ethics of communication, ethics learning activities, ethics of specific subdisciplines, ethics of war, ethics workshops, nation or culture-specific discussions, pedagogy, specific ethics case studies, student assessment in ethics, theology
Qualifying results counts	28	10	15	24	38
Unique qualifying result count (shared results across multiple columns counted only once)	← 106 →				

Note: "*" represents wildcard search character (e.g., "engineer*" indicates "engineering," "engineers," "engineer," etc.).

(or straining the unity of) engineering practice. Search 1's results count, qualification criteria, and the topic areas of sources excluded during the qualification process are also summarized in Table 1.

Content analysis of Search 1 results began with high-level topic categorization to document the unique areas of scholarship from which sources were drawn. Here, we established six categories: (1) historical reviews of engineering practice and education, (2) analyses of organizational aspects of engineering work and careers, (3) literature on gender and engineering professional identity, (4) analyses of the development of engineering norms and standards, (5) discussion of societal and occupational expectations of engineers, and (6) engineering ethics textbooks. We allowed for sources to reside in multiple categories. Content analysis of the qualified sources first entailed each coauthor's independent review of the body texts to identify substantiating argument(s) made in support of or against the case of professional unity. The coauthors then generated thematic cluster statements to

TABLE 2 Search 1 results: Attributes that unify and dis-unify engineering practice

		What attributes are discussed as unifying or dis-unifying engineering practice?	
Source topic area	**Supporting sources**	**Unifying**	**Dis-unifying**
Historical reviews of engineering practice and the education system	Layton (1971); Noble (1977); Meiksins (1988); Reynolds (1991); Meiksins and Smith (1993); Kemper and Sanders (2001); Lawson (2002); Pursell (2006); Auyang (2006); Kline (2008); Jones (2011); Verin and Gouzevitch (2011); Diogo and de Matos (2012)	– Formalization of craft practices into codified practices – Campaigns for professional unity – Broad societal need for services	– Lack of consensus understanding of engineering work in society – Lack of universal recognition of professional bounds by society, employers, and practitioners – Societal confusion about roles of scientists versus engineers
	Ferrall (1995); Thom (1998); Williams (2002); Downey and Lucena (2004); Downey (2005); Sørensen (2009); Jamison (2013)		– Technological change prompting hybridization and reformulation of work – Dynamic expectations of engineers' duties or required skills
	Grayson (1980); National Research Council (1985); Dreicer (1995); Seely (1995); Vest (1995); Thom (1998); Seely (1999); Downey and Lucena (2004); NAE (2005); Lucena et al. (2008); Heywood (2009); Sheppard et al. (2009); Atman et al. (2010); Grasso and Burkins (2010); Jamison (2013); Crawley et al. (2014)	– Attempts to establish (national, global) standards and approaches for engineering education	– Ongoing discourse about the need for improved engineering curricular alignment (e.g., reconciliation of academia, practitioner, industry leader perspectives) – Ongoing debate about missing, over-, and under-represented curricular components
Analyses of organizational aspects of engineering work and careers (20th–21st century)	Burke (1969); Meiksins and Watson (1989); Ferrall (1995); Yip and Rowlinson (2009)	– Job and task definitions, job norms, and role structures established (e.g., that engineers have embraced) – Acknowledged need to stay current with disciplinary, project, or product knowledge	– Job, role, task, and project definition sometimes formulated outside the control of engineers (e.g., such as project schedules)
	Ritti (1968); Perrucci and Gerstl (1969); Kerr et al. (1977); Child and Fulk (1982); Bailyn and Lynch (1983); Rynes et al. (1988); Bacharach et al. (1990); Reynolds (1991); Meiksins and Smith (1993); Igbaria et al. (1999); Holt (2001)	– Specialized knowledge and skill requirements tied to job roles	– Organizations, rather than a centralized engineering profession, define job details and expectations – Career advancement paths are established by individual organizations rather than by a centralized engineering profession
	Watson and Meiksins (1991); Perlow and Bailyn (1997); Newberry (2007)	– Specialized knowledge and skill requirements tied to job roles	– Engineers identify with their (varied) work or technology specialty itself, rather than with a unified professional identity
	Goldner and Ritti (1967)	– Specialized knowledge and skill requirements tied to job roles	– Engineers face career mobility incentive to avoid professional unification

(Continues)

TABLE 2 (Continued)

Source topic area	Supporting sources	What attributes are discussed as unifying or dis-unifying engineering practice?	
		Unifying	**Dis-unifying**
Literature on gender and engineering professional identity (21st century)	Jorgenson (2002); Faulkner (2009); Cech et al. (2011); Ayre et al. (2013); Herman (2015); Cech (2015)	– Perceived need for entry/ acceptance into engineering profession – Specific job expectations perceived as associated with engineering (e.g., level of commitment at job, capabilities required)	– Career identity as personally, rather than professionally, defined – Career identity as construed through a variety of adjustments and positionings, rather than through a unified concept of an engineering practitioner
Analyses of the development of engineering norms and standards	Gerstl and Hutton (1966); Noble (1977); Lawson (2002); Auyang (2006); Keltikangas and Martinsuo (2009); Gainsburg et al. (2010); Kedrowicz and Sullivan (2012)	– Development of engineering standards – Responsibility for producing specific artifacts (e.g., technical drawings, software code) in accordance with standards – Socialization of unique ways of thinking and communicating as engineers	
Discussion on societal and occupational expectations of engineers	Johnson (1991); Davis (2001); Herkert (2001); Kemper and Sanders (2001); Spier (2001); Martin (2002); Vesilind (2002); Antoniou et al. (2007); Downey et al. (2007); Frey and O'Neill-Carrillo (2008); Harris (2008); Lucena and Schneider (2008); Son (2008); Stovall (2011); Diogo and de Matos (2012); Didier and Derouet (2013); Michelfelder and Jones (2013)	– Responsibilities to one's community, nation, and/or world for public safety, health, welfare, and the environment	– Sense of social obligation not consistent across all groups of engineers or time periods; not consistently integrated into engineering education
	Kemper and Sanders (2001); Auyang (2006); Trevelyan (2010); Gainsburg et al. (2010); Dias (2014); Schmidt (2014)	– Responsibility for documenting, communicating, and collaborating about designs and associated risks, issues, and concerns with stakeholders, other engineers, and/or adjacent functions	
	Lynch and Kline (2000); Kemper and Sanders (2001); Auyang (2006); Delahousse (2009); Basart and Serra (2013); Schmidt (2014); Hayes (2015); Lurie and Mark (2016)	– Responsibility for outcomes and consequences of design and development projects; responsibility to address failures of designs	
	Kiepas (1997); Gotterbarn (1999); Kemper and Sanders (2001); Harris (2008); Dias (2014); Lurie and Mark (2016)	– Responsibility for (and attention to) minute details, and the associated risks and broader implications of such details	
	Gotterbarn (1999); Kemper and Sanders (2001); Martin (2002); Downey et al. (2007); Walesh (2012); Brauer (2013); Michelfelder and Jones (2013); Schmidt (2014); Schlossberger (2016)	– Formal codes of professional ethics published by engineering disciplines' societies	– Ethics codes may be incomplete, inconsistently revered, inconsistently integrated into engineering education

TABLE 2 (Continued)

Source topic area	Supporting sources	What attributes are discussed as unifying or dis-unifying engineering practice? Unifying	Dis-unifying
Engineering ethics textbooks	Schlossberger (1993); Unger (1994); Beder (1998); Vesilind and Gunn (1998); Fleddermann (2004); Martin and Schinzinger (2005); Robinson et al. (2007)	– Professional societies are in place representing the major engineering subdisciplines	– Professional societies are relatively weak (e.g., compared to those of other established professions such as medicine and law) – Incomplete adoption of society membership or licensing among engineers
	Unger (1994); Pinkus (1997); Vesilind and Gunn (1998); Armstrong et al. (1999); Humphreys (1999); Fleddermann (2004); Martin and Schinzinger (2005); Robinson et al. (2007); McCuen and Gilroy (2011); Whitbeck (2011); Harris et al. (2013); Bowen (2014); Catalano (2014)	– Published codes of engineering ethics share common themes, such as: – Acceptance of responsibility to protect safety, health, and welfare of the public – Commitment to practice only in areas of competence; to defer to experts otherwise – Commitment to honesty and objectivity	
	Unger (1994); Pinkus (1997); Beder (1998); Fleddermann (2004); Govindarajan et al. (2004); Martin and Schinzinger (2005); Baura (2006); Pfatteicher (2010); Whitbeck (2011); Harris et al. (2013)	– Responsibility for (and attention to) minute design details, and the associated risks and broader implications of such details (e.g., discussed here as "preventative ethics")	

encompass arguments supported by groups of related or complementary sources (Krippendorff, 2004), first identifying clusters pertaining to evidence for unity across engineering practice and next discerning those evidencing dis-unity across practice. The final set of cluster statements represents a reconciliation of each coauthor's individual analysis. Table 2 summarizes the content analysis for the Search 1 results. To present findings compactly, we have arranged the results so that "unifying" and "dis-unifying" themes could be presented side by side when possible.

Table 2, thus, presents a collection of discussions supporting or contesting engineering's professional cohesion. Arguments in support of cohesion cite such elements of engineering work as specialized knowledge and skills, conventions, standards, and many others. Among these findings, a particular indication of cohesion uniquely stands out as both being discussed recurrently and being met with minimal contestation in this literature set: engineering practitioners' design responsibility—their responsibility for the effectiveness and safety of products through governance of design (new or existing). Notably, the literature review methods employed cannot demonstrate an absence of counterargument to this claim of cohesion, only that there does not appear to be a substantial one among retrieved sources. Accordingly, we do not claim to prove what unifies engineering occupations; rather, we report on the conventionality and prevalence of design responsibility as a unifying occupational criterion based on this literature. Example statements from among sources in Table 2 provide illustrations in part of design responsibility:

- "Responsible engineers are expected to foresee … consequences [of design decisions]" (Whitbeck, 2011, p. 178).
- "When something goes wrong on an engineering project, the responsibility falls heavily on engineers" (Basart & Serra, 2013, p. 181).

- “Engineers can expect to be held accountable, if not legally liable … for caused harms” (Harris et al., 2013, p. 50).
- “Attention to detail is a watchword of the engineering profession” (Dias, 2014, p. 545).
- “The engineer thus assumes a responsibility to determine which dangers are pertinent to each [design] … to decide how to best deal with them ” (Schmidt, 2014, p. 998).

Among other attributes put forth in the literature as evidence of unity in engineering, demands for specialized knowledge and skills also received notable discussion (Table 2). Counterarguments about this attribute cite the ever-growing diversity of technical specialties across roles and over time as well as diverse employers' independent influences over knowledge and skill requirements (e.g., outside the governance of unifying institutions). Relatedly, the reviewed literature also cites broad efforts at engineering educational standard setting over the past century while calling attention to associated debates and the continued evolution of standards. Meanwhile, the other remaining assertions about professional unity in engineering reported in Table 2 received comparably less support or met greater contestation compared to the notion of design responsibility.

We proceed by inferring that design responsibility is a recognized component of what it means to fulfill an engineering role without concluding that it is the sole factor unifying engineering practice. We assume rather that it is a condition of work prevalently acknowledged as “engineering” and can reasonably serve as a key identifier of engineering occupations for purposes of anchoring an occupational outcomes typology. This result from Search 1 informed the search question for Search 2.

3.1.2 | Search 2: Identifying job functions involved in carrying out attribute(s) of engineering practice

> **Search question**: *Among literature that discusses design responsibility of engineering practitioners, which of practitioners' job functions does this literature identify as being involved in upholding design responsibility?*

As follows from Search 1's results, in Search 2, we sought evidence of where design responsibility manifests in engineering practice (i.e., through which job functions is design responsibility upheld?). We narrowed the search date range to 1990–2016 to capture a contemporary discussion of practice. We then ran two subrounds of search differentiated by the first's broad inquiry into literature describing engineering design responsibility and the second's specific inquiry into ethnographic accounts of product development workplaces. We employed the subject terms, text terms, and search logic as summarized in Table 3. The search's qualification review verified that sources described engineers' job responsibilities in practice contexts. The results count, qualification criteria, and the resultant topic areas of excluded sources from Search 2 are summarized in Table 3.

Search 2's content analysis identified broad areas where design responsibility appears in engineering occupations, setting the stage for the follow-on search's (Search 3) narrower focus on finding specific tasks or activities within those areas. For Search 2's qualified sources, each coauthor reviewed the body text to locate discussions about design responsibility and to identify the associated area of practice that the discussions ascribed this responsibility to; we label these general areas of practice as “job functions” constituting engineering occupations. The job function names and associated sources reflect a reconciliation of the two authors' separate content analyses. Several job functions pertaining to design responsibility were identifiable in the literature; however, as we show, three of these were discussed notably more often than the others. Table 4 summarizes the results of Search 2's content analysis, listing the identified job functions along with the supporting sources for each.

Although the literature uses the word “responsibility” throughout descriptions of engineering practice, our content analysis finds that much of design responsibility is encompassed by engineers' job functions of (1) design formulation; (2) configuration control of designs (e.g., control of design releases, design changes, and key substantiating design information); and (3) issue, error, or failure detection and response. Search 2 also produced a disjointed variety of other results beyond these three job function clusters; clearly, engineers' design responsibility can manifest in many areas. Yet given this search's aim of establishing highest-confidence areas of “where to look” for design responsibility enacted in practice, we focused the subsequent search (Search 3) on identifying activities within these three job functions. Example statements from sources listed in Table 4 illustrate design responsibility's manifestation within the three areas:

TABLE 3 Search 2 criteria and results count: Sources discussing design responsibility of engineers

	Subrounds of search	
	1	2
Subject search terms	engineer*	engineer*, [design OR "product development"]
Body text search terms	engineer*, design, responsibilit*	engineer*, ethnograph*, responsibilit*, [work OR practice]
Subject exclusion terms	← "K-12," counseling, "high school," immigration, marketing, parent* →	
Media	← academic journal articles & books →	
Date range	← 1990–2016 →	
Raw results counts	962	365
Qualification:		
Inclusion criteria	← Source must discuss engineers' job responsibilities → ← Source must reference engineering practice context(s) →	
Primary topics of excluded sources	corporate ethics, corporate social responsibility, descriptions of subdiscipline-specific technical issues, psychology	educational design, ethnography as part of the design process, ethnography as a design tool, descriptive literature on workplaces (e.g., general focus rather than on engineering jobs, tasks, or responsibilities)
Qualifying results counts	48	11
Unique qualifying result count (shared results across multiple columns counted only once)	← 56 →	

Note: "*" represents wildcard search character (e.g., "engineer*" indicates "engineering," "engineer," etc.).

Design formulation:

> "Engineers have the primary responsibility for making a product, machine, or system work in accord with established design criteria" (Main, 2002, p. 28).
>
> "Detailed design is primarily the responsibility of discipline-specific engineers" (Burk, 2011, p. 202).

Configuration control of designs:

> "Problems ... can arise from implementing [a design change]. ... The responsibility for these problems is usually placed squarely on the shoulders of the design engineer" (Wright, 1997, p. 37).
>
> "Engineers coordinate, monitor, and evaluate work ... adapting plans and organization to circumstances" (Trevelyan, 2010, p. 189).

Issue, error, or failure detection and response:

> "[Engineers] diagnose perceived performance deficiencies (or failures), conceive and design remediation works, and predict how well the modified system will perform" (Trevelyan, 2010, p. 189).
>
> "[Software engineers] take responsibility for detecting, correcting, and reporting errors in software and associated documents on which they work" (Gotterbarn, 1999, p. 88).

These three job function areas identified in Search 2 informed the search question for Search 3.

TABLE 4 Search 2 results: Job functions encompassing engineers' design responsibility

Sources discussing engineering job functions through which "design responsibility" manifests in practice	Job functions discussed: Engineering design formulation (including design verification)	Job functions discussed: Configuration control of designs (e.g., managing engineering changes)	Job functions discussed: Issue, error, or failure detection and response	Job functions discussed: Other (e.g., manufacturing oversight; training or teaching; informing society)	Engineering discipline observed/ discussed
Avvakumovits (1996)		X			Civil
Baird et al. (2000)	X		X		Mechanical
Beder (1998)	X		X		General
Bibby et al. (2006)	X	X			Civil
Brown (2007)			X		General
Bucciarelli (1994)	X	X	X		General
Bucciarelli (2002)	X				Mechanical, electrical
Burk (2011)	X	X	X	X	Systems
Coeckelbergh (2006)	X				General
Collin (2004)	X				General
Cunningham et al. (2013)	X				General
Filho and Kaminski (2009)	X	X		X	Mechanical
Fleischer and Liker (1992)	X				Mechanical
Gainsburg et al. (2010)	X				Civil
Galpin et al. (2007)				X	General
Gillum (2000)	X	X	X		Civil
Gotterbarn (1999)	X	X	X	X	Software
Hailpern and Santhanam (2002)	X		X		Software
Hall (2009)	X				Software
Hayes (2015)	X				Civil
Hwang et al. (2009)		X			General
Jack (2013)	X		X	X	General
Jackson and Hundley, Jr. (2004)			X		Civil
Jemielniak (2007)	X				Software
Karlsson et al. (2008)	X	X			Civil
Kemper and Sanders (2001)	X		X		General
Kunda (2006)	X				General
Le May and Le May (2016)			X		Civil
Lindsay (2002)	X				General
Loui (1998)	X				General
Loulakis and McLaughlin (2016)	X		X		Civil
Main (2002)	X				General
Millet (1999)			X		Civil
Nethercot (2008)	X				Civil
Onarheim (2012)	X				Mechanical

TABLE 4 (Continued)

Sources discussing engineering job functions through which "design responsibility" manifests in practice	Job functions discussed: Engineering design formulation (including design verification)	Configuration control of designs (e.g., managing engineering changes)	Issue, error, or failure detection and response	Other (e.g., manufacturing oversight; training or teaching; informing society)	Engineering discipline observed/ discussed
Pahl et al. (2007)	X	X	X	X	General
Pesch (2015)	X				General
Pfatteicher (2000)		X	X		Civil
Robinson (2000)	X			X	Civil
Roeser (2012)	X				General
Rowland and Rowland (1995)	X				Software
Shankar et al. (2012)		X			Mechanical
Suchman (2000)	X				Civil
Swierstra and Jelsma (2006)	X				General
Trevelyan (2007)	X	X	X	X	General
Trevelyan (2010)	X	X	X	X	General
Van de Poel and Royakkers (2011)	X		X		General
Van de Poel and Van Gorp (2006)	X				General
Vinck et al. (2003)	X	X	X	X	General
Waelbers (2011)	X				General
Walesh (2012)	X	X	X	X	Civil
Whitbeck (2011)	X		X		General
Wirfs-Brock (2009)	X	X	X		Software
Workman (1995)	X			X	Computer
Wright (1997)		X			General
Yogeswaran and Kumaraswamy (1999)				X	Civil

3.1.3 | Search 3: Identifying work activities that compose the job functions of engineers

> **Search question**: *Among literature that discusses the engineering job functions of design formulation; configuration control of designs; and issue, error, or failure detection and response, what specific work activities does this literature identify as composing these job functions?*

In Search 3, we employed a date range from 1990 to 2016 and configured the search to identify specific work activities that compose the job functions established in Search 2. Here, we ran three subrounds of search utilizing the search criteria summarized in Table 5, each pertaining to one of the three job functions. Search 3's qualification review verified that sources discussed details of real-world engineering work practices. Its results count, qualification criteria, and topic areas of excluded sources are summarized in Table 5.

Content analysis for Search 3 involved a two-level source-sorting approach similar to that employed in Search 1. Here, the high-level topic bins were preestablished by the job functions identified in Search 2. For all sources, each coauthor separately reviewed body texts to identify discussions of specific activities involved in carrying out the subject job functions. We employed clustering analysis for group-related sources; in this case, the clustered themes take the form of specific job activities discussed among sources. Again, cluster statements resulted from reconciling coauthors'

TABLE 5 Search 3 criteria and results count: Sources discussing job functions of engineers

	Subrounds of search		
	1	2	3
Subject search terms	engineer*, (design OR "product development")	engineer*	engineer*
Body text search terms	engineer*, "design process," responsibility*, role	engineer*, ["change management" OR "change control" OR "configuration management" OR "design change"]	engineer*, [failure OR error], [prevention OR process]
Subject exclusion terms	← "K-12," counseling, "high school," immigration, marketing, parent* →		
Media	← academic journal articles & books →		
Date range	← 1990–2016 →		
Raw results counts	437	879	636
Qualification:			
Inclusion criteria	← Source must discuss engineering work process or practice details → ← Source must reference engineering practice contexts →		
Primary topics of excluded sources	architecture, curricula, manufacturing processes, pedagogy, product portfolio management, specific environmental issues, subdiscipline specific design process (e.g., genetics, nanomaterials)	automation, communication networks, cost control, curricula, government, legal and contractual issues, mathematical algorithms, policy, predictive modeling, specific commercial software packages	contingency planning, financial impacts of design failure, injuries/accidents in industrial plants, materials failure analysis (e.g., microscopy, specimen testing), predictive modeling, robustness algorithms, system diagnostics and prognostics
Qualifying results counts	50	43	24
Unique qualifying result count (shared results across multiple columns counted only once)	← 112 →		

Note: "*" represents wildcard search character (e.g., "engineer*" indicates "engineering," "engineers," "engineer," etc.).

separate analyses. Table 6 summarizes the content analysis of Search 3's results, taking the form of a list of job activities tied to design responsibility that literature commonly associates with engineering occupations.

The activities listed in Table 6 highlight engineering practitioners' involvement in carrying out design processes, conducting analyses, communicating design information, collaborating and coordinating, managing changes, monitoring for failures, and rectifying issues or errors as they uphold design responsibility during various product lifecycle stages. As thematic clustering methods such as those employed here do an injustice to sparse or more nuanced discussions within the literature, we do not purport that these activities comprehensively or universally illustrate design responsibility in engineering roles. Rather, these activities reflect prominently documented examples of how design responsibility is enacted in engineering practice according to literature. Results from Search 3 inform our search for contemporary occupational roles similar or related to engineering roles (Search 4).

3.1.4 | Search 4: Identifying occupations involving similar or related work activities as engineers

> **Search question**: *Among the documented set of present-day occupations, which of them show evidence of similar work activities to those identified in engineering roles in Search 3 beyond those occupations with the word "engineer" in their titles?*

TABLE 6 Search 3 results: Work activities composing engineers' design responsibility

Topic area	Supporting sources	Emergent themes: Work activities through which design responsibility manifests in practice
Engineering design formulation	Ichida and Voigt (1996); Magrab (1997); Adams (1999); Samuel and Weir (1999); Murdoch and McDermid (2000); Armstrong (2001); Main (2002); Annacchino (2003); Anderson (2004); Ciambrone (2007); Hart (2007); Pahl et al. (2007); Cross (2008); Dym et al. (2009); Eder and Hosnedl (2010); Jones (2010); Benavides (2012); Dieter and Schmidt (2012); Ćatić and Malmqvist (2013); Weiss (2013); Williams and Johnson (2013); Britton and Torvinen (2014); Mital et al. (2014); Horenstein (2015); Ulrich and Eppinger (2016)	– Engineers follow processes or protocols that impose checks upon their designs (e.g., design reviews, peer reviews, stakeholder reviews, drawing reviews, code reviews, verification testing, qualification testing) to verify that designs are on track to achieve objectives (e.g., effectiveness, safety, producibility, serviceability)
	Pugh (1991); Magrab (1997); Skalak et al. (1997); Hazelrigg (1998); Cather et al. (2001); Annacchino (2003); Dick (2006); Hatamura (2006); Morgan and Liker (2006); Pahl et al. (2007); Park (2007); Cross (2008); Dym et al. (2009); Eder and Hosnedl (2010); Cussler and Moggridge (2011); Haik and Shahin (2011); Benavides (2012); Dieter and Schmidt (2012); Cadden and Downes (2013); Weiss (2013); Britton and Torvinen (2014); Mital et al. (2014); Cobb et al. (2016); Ullman (2016); Ulrich and Eppinger (2016)	– Engineers commit to a thorough consideration of possible solution concepts before deciding upon the best concept suited to meet identified users' and/or customers' needs, and thus to be carried forward into design realization
	Ichida and Voigt (1996); Moss (1996); Twigg (1998); Armstrong (2001); Annacchino (2003); Lloyd and Busby (2003); Anderson (2004); Ciambrone (2007); Pahl et al. (2007); Allard et al. (2009); Dym et al. (2009); Maier et al. (2009); Eder and Hosnedl (2010); Holt and Barnes (2010); Jones (2010); Dieter and Schmidt (2012); Pavković et al. (2013); Weiss (2013); Britton and Torvinen (2014); Mital et al. (2014); Monticolo et al. (2014); Horenstein (2015); Ullman (2016); Ulrich and Eppinger (2016)	– Engineers accept responsibility for documentation and communication of design information, including design definition (e.g., drawings, schematics, source code) and design rationales (e.g., key assumptions, analyses, and trade-offs that drove the designs)
	Moss (1996); Magrab (1997); Twigg (1998); Jeng and Eastman (1999); Armstrong (2001); Monplaisir and Singh (2002); Annacchino (2003); Anderson (2004); Morgan and Liker (2006); Ciambrone (2007); Pahl et al. (2007); Dym et al. (2009); Maier et al. (2009); Holt and Barnes (2010); Whyte and Lobo (2010); Zirpoli and Becker (2011); Cussler and Moggridge (2011); Benavides (2012); Dieter and Schmidt (2012); Cataldo and Herbsleb (2013); David (2013); Weiss (2013); Britton and Torvinen (2014); Horenstein (2015); Ullman (2016); Ulrich and Eppinger (2016)	– Engineers engage in collaboration and coordination routines in order to enact designs that accommodate the aggregate needs and/or capabilities of the other participatory stakeholders in the product value creation process (e.g., other engineers or engineering teams, manufacturing, supply chain, marketing)
Configuration control of designs	Buckley (1996); Wright (1997); Terwiesch and Loch (1999); Dart (2000); Lyon (2000); Haug et al. (2001); Keyes (2004); Moreira (2004); Jarratt et al. (2005); Jarratt et al. (2006); Watts (2008); Watts (2010); Jarratt et al. (2011); Shankar et al., 2012); Veldman and Alblas (2012); Hamraz, Caldwell, and Clarkson (2013); Reddi and Moon (2013); Leon (2015); Quigley and Robertson (2015); Watts (2015); Aiello and Sachs (2016)	– Engineers follow organized and controlled processes to release new product designs and to subsequently make changes to these designs. Engineers' hold (or share) design change approval responsibilities as part of these processes

(Continues)

TABLE 6 (Continued)

Topic area	Supporting sources	Emergent themes: Work activities through which design responsibility manifests in practice
	Wright (1997); Lyon (2000); Haug et al. (2001); Eckert et al. (2004), Keyes (2004); Jarratt et al. (2005); Jarratt et al. (2006); Scholz-Reiter et al. (2007); Watts (2008); Hansen and Gammel (2008); Mohan et al. (2008); Rovegård et al. (2008); Fei et al. (2011); Jarratt et al. (2011); Koh et al. (2011); Manuele (2012); Ahmad et al. (2013); Hamraz, Caldwell, and Clarkson (2013); Hamraz, Caldwell, Wynn, and Clarkson (2013); Leon (2015); Quigley and Robertson (2015); Watts (2015); Aiello and Sachs (2016)	– Before changing or correcting a design, engineers analyze the proposed change for any potential adverse impacts to baseline product performance
	Lyon (2000); Haug et al. (2001); Berczuk and Appleton (2002); Keyes (2004); Mohan et al. (2008); Shiau and Wee (2008); Kocar and Akgunduz (2010); Watts (2010); Son et al. (2014); Papinniemi et al. (2014); Monticolo et al. (2015); Subrahmanian et al. (2015); Leon (2015); Quigley and Robertson (2015); Watts (2015); Aiello and Sachs (2016); Morris et al. (2016)	– Engineers utilize design baseline management information systems to store and control design data, manage design data access, and facilitate design change traceability in collaborative design environments
	Wright (1997); Lyon (2000); Haug et al. (2001); Keyes (2004); Scholz-Reiter et al. (2007); Quintana et al. (2012); Reddi and Moon (2013); Han et al. (2015); Quigley and Robertson (2015); Watts (2015); Morris et al. (2016); Aiello and Sachs (2016)	– Throughout a product's lifecycle, engineers assess design information accuracy, integrity, and applicability, while working to prevent information conflicts, and overseeing timely dissemination of design baseline updates and change information to stakeholders (e.g., via a design baseline management information system)
Issue, error, or failure detection and response	Petroski (1994); Millet (1999); Busby and Strutt (2001); Keil and Robey (2001); Evan and Manion (2002); Busby and Coeckelbergh (2003); Davidson and Labib (2003); Kardon (2005); Lee et al. (2006); Pahl et al. (2007); Boin and Schulman (2008); Savoie and Frey (2012); Cataldo and Herbsleb (2013); Williams and Johnson (2013); Horenstein (2015); Williams and Johnson (2015)	– Engineers continually monitor designs and design processes for possible errors, issues, and potential failure modes throughout the product lifecycle, advocating for changes when necessary
	Petroski (1994); Gillum (2000); Moncarz and Taylor (2000); Evan and Manion (2002); Pahl et al. (2007); Wearne (2008); Willis (2009); Lopez et al. (2010); Love et al. (2013); Fehr (2012); Horenstein (2015); Le May and Le May (2016)	– Engineers commit to determining root causes of failures that have occurred (or to cooperating with investigators of such failures) and to following up with design, implementation, standards, and/or process corrective actions

Search 4 was conducted in September 2017 within the O*Net database to retrieve occupational titles and descriptions. O*Net is a large-scale, searchable occupations database encompassing more than 58,000 occupation titles (called “alternate” or “lay” titles) linked to approximately 1000 primary occupation entries with detailed descriptions (O*Net, 2017). O*Net is hosted by a US government-funded research center but is increasingly utilized globally (Hanna et al., 2019, p. 600–607).

In Search 4, we sought to identify occupations in close proximity to conventional engineering roles—engineering's “nearest neighbors”—by searching for jobs composed of similar work activities as engineering roles yet not titled as such. We conducted a keyword search based on criteria listed in Table 7. These criteria center upon the themes of *carrying out design processes*, *conducting analyses*, *communicating design information*, *collaborating and coordinating*, and *managing changes* uncovered in Search 3 (as exceptions, we avoid the terms “error” or “failure” due to their varied usage contexts across job descriptions). As expected, jobs with the word “engineer” in their title dominated the top of the search results list. We began by filtering the results to remove those titled as “engineer.” We next removed jobs

TABLE 7 Search 4 criteria: Occupations in close proximity to engineering roles

	Occupations search query
Search terms	engineer*, design*, process, analyze, communicate, [collaborate OR coordinate], [change OR configuration]
Database	Occupation*NET Database (https://www.onetonline.org/find)
Date of search	September, 2017
Exclusion filters	Occupations with "engineer" in job title Occupations requiring less than a bachelor's degree Architect occupations Teaching occupations
Results count (based on cutoff threshold)	100 (primary job titles) 1100 (primary job titles + top-10 alternate titles for each)

Note: "*" represents wildcard search character (e.g., "engineer*" indicates "engineering," "engineers," "engineer," etc.).

requiring less than a bachelor's degree given our focus on occupations most likely to carry responsibilities similar to conventionally designated engineering jobs and to be pursued by engineering students. We also removed the jobs in teaching and building and landscape architecture fields due to their association with specific occupation groups. Finally, we retained the 100 remaining results (primary occupation titles) in rank order of relatedness to the search terms (for a description of O*Net's rank-ordering algorithm, refer to Morris, 2017). For each of the 100 retained titles, we included the top 10 listed alternate titles reported by O*Net. Search 4, thus, produced a list of 1100 present-day nonengineering-titled occupations bearing a relatively strong relationship to engineering roles compared to other occupations. The full list of these occupational titles can be found in the online supplemental information.

Results qualification methods for Search 4 were distinct from the other searches given its examination of a jobs database rather than a literature set. Although results were systematically retrieved, discretion was needed to establish a cutoff threshold bounding the set of nearest-matching results because the O*Net algorithm would otherwise continue to report all results in its database in decreasing order of relatedness to the search terms. We opted to evaluate setting this threshold at 100 primary job titles and tested the robustness of this choice by conducting a preliminary results clustering analysis to ensure that no prominent job clusters were curtailed due to the threshold. As expected, job titles became increasingly unrelated to one another with increased distance down the results list. In reviewing the next 50 jobs beyond the threshold, we were unable to discern any clusters of more than four related positions among them. We concluded that jobs beyond the threshold are sparsely related and that our threshold choice supports our goal of being able to discern prominent occupational groups in closest proximity to traditional engineering jobs.

We next carried out a full content analysis on Search 4's results, identifying the clusters of related jobs from among the qualified results based on titles and their accompanying job description summary statements (short descriptions atop each O*Net database entry) to arrive at four occupation clusters: developers (in software or computer contexts), designers, coordinative and managerial roles, and analysts and technical communicators. Table 8 presents a summary of Search 4's content analysis where each column delineates an occupation cluster and contains several example constituent job titles, one of which is expanded as a detailed example. While the results in Table 8 do not establish which of these jobs should be considered "engineering" jobs, we assume that this set of roles is representative of engineering's "nearest neighbor" occupations.

In sum, this sequential literature review provided substantiation for developing propositions to underpin a typology of occupations' engineering relatedness. The review identified a unifying occupational attribute in engineering (based on Search 1; 106 qualified sources), discerned primary job functions that underlie this unifying attribute (based on Search 2; 56 qualified sources), and identified work activities representative of how these job functions likely manifest in practice (based on Search 3; 112 qualified sources). Across Searches 1, 2, and 3, a total of 259 unique (nonrepeated) sources were analyzed. Finally, we used the findings from Searches 1, 2, and 3 to identify common types of contemporary nonengineering-titled roles that exist in near proximity to engineering roles (i.e., Table 8, based upon Search 4). We proceed in *Typology Synthesis and Discussion* to present a framework for relating such "nearest neighbor" roles to traditional engineering roles and to roles of more distant proximity to engineering.

TABLE 8 Search 4 results: Nonengineering-titled occupations sharing attributes with engineering roles

Job title clusters:	**Developers—software or computer context**	**Designers**	**Coordinative and managerial roles**	**Analysts and technical communicators**
Example job titles from cluster	– Software application developers	– Industrial designers	– Project managers (c)	– Computer systems analysts
	– System software developers	– Designers (a)	– Product/systems development Managers (d)	– Operations research analysts
	– Web developers	– Design directors	– Managers (e)	– Decision analysts
	– Computer network architects	– Systems designers (b)	– Leads (f)	– Sustainability analysts
	– Software architects	– Environmental designers	– Directors (g)	– Technical writers
	– Network developers	– Interface designers	– Chief technical officers	– Technical editors
Details of select example:	**Software application developers**	**Industrial designers**	**Project managers**	**Computer systems analysts**
Description	Develop, create, and modify general computer applications software or specialized utility programs. Analyze user needs and develop software solutions. Design software or customize software for client use with the aim of optimizing operational efficiency. May analyze and design databases within an application area, working individually or coordinating database development as part of a team. May supervise computer programmers.	Develop and design manufactured products such as cars, home appliances, and children's toys. Combine artistic talent with research on product use, marketing, and materials to create the most functional and appealing product design.	Plan, initiate, and manage projects. Lead and guide the work of technical staff. Serve as liaison between business and technical aspects of projects. Plan project stages and assess business implications for each stage. Monitor progress to assure deadlines, standards, and cost targets are met.	Analyze science, engineering, business, and other data processing problems to implement and improve computer systems. Analyze user requirements, procedures, and problems to automate or improve existing systems and review computer system capabilities, workflow, and scheduling limitations. May analyze or recommend commercially available software.
Primary tasks	– Modify existing software to correct errors or to improve its performance	– Prepare sketches of ideas, detailed drawings, illustrations, artwork, and blueprints	– Manage project execution to ensure adherence to budget, schedule, and scope	– Test, maintain, and monitor computer programs and systems, including coordinating the installation of computer programs and systems
	– Analyze user needs and requirements to determine feasibility of designs	– Confer with engineering, marketing, production, or sales departments, or with customers	– Develop or update project plans, including information such as objectives, technologies, systems, specifications, schedules, funding, and staffing	–Troubleshoot program and system malfunctions to restore normal functioning
	– Confer with systems analysts, engineers,			

TABLE 8 (Continued)

Details of select example:	Software application developers	Industrial designers	Project managers	Computer systems analysts
	programmers and others to design systems	– Modify and refine designs using working models	– Monitor or track project milestones and deliverables	– Expand or modify system to serve new purposes or improve work flow
	– Store, retrieve, and manipulate data for analysis of system capabilities and requirements	– Direct and coordinate the fabrication of models or samples	– Confer with project personnel to identify and resolve problems	– Use computers in the analysis and solution of business problems such as development of integrated production and inventory control and cost analysis systems
	– Design, develop, and modify software systems using scientific analysis and mathematical models to predict and measure outcome and consequences of design	– Evaluate feasibility of design ideas	– Develop and manage work breakdown structures of projects	– Consult with management to ensure agreement on system principles
Primary work styles	– Analytical thinking – Attention to detail – Innovation – Integrity – Achievement/effort	– Innovation – Attention to detail – Analytical thinking – Persistence – Dependability	– Leadership – Initiative – Persistence – Attention to detail – Dependability	– Analytical thinking – Attention to detail – Adaptability/flexibility – Dependability – Integrity

Note: 1—Column headings represent the four primary occupation clusters discerned in Search 4.
2—Example Job Titles are taken from among the primary and alternate job titles retrieved from the *Occupation Information Network* (*O*Net*) as specified in Table 7 (refer to URL and search parameters).
3—Example Job Details are excerpted from *O*Net* database entries for the first example given in each category; in the case of project managers where there are multiple entries, verbiage is taken from the IT Project Manager profile.
4—Primary Tasks and Primary work Styles: excerpted from the O*Net detailed occupational profile of the subject job; the top 5 attributes in the database are shown for both Tasks and Work Styles.
5—Curtailed job titles are presented for those with multiple similar entries in the database; the notes below explain how the curtailed titles are often used as the root of longer titles: (a) "Designer" is a recurrent job title root in the results set, referencing various product development contexts. Examples titles include "Automotive Designers," "Bicycle Designers," "Boat Designers," "Athletic Shoe Designers," and so forth. (b) Examples of "Systems Designer" roles in the results set include "Computer Systems Designers" and "Industrial Green Systems Designers." (c) "Project Manager" roles are usually preceded by discipline modifiers in the results set. Examples include "Information Technology Project Managers," "Energy Project Managers," "Construction project Managers," "Transportation project Managers," and so forth. (d) "Product Manager," "Product Development Manager," and "System Development Manager" are listed in the results set in reference to computing and alternative energy contexts. (e) "Manager" is a recurrent job title root in the results set. Examples titles include "Software Development Manager," "Compliance Manager," "Information Security Manager," "Technical Manager," "Sustainability Manager," and others. (f) "Lead" is a recurrent job title root in the results set. Examples include "Systems Applications Programming Lead," "Lead Simulation Modeler," "Energy Projects Lead," "Software Development Team Lead," "Computer Network Specialist Lead," and others. (g) "Director" is a recurrent job title root in the results set. Example titles include "Web Development Director," "Planning Director," "Construction Director," "Water Resources Program Director," "Technology Director," and others.

3.2 | Limitations of methods and results

Methods employed in this study have known limitations. Our systematic literature review necessarily considered wide time ranges and drew generalized inferences from large quantities of search results. We utilized thematic clustering analysis (Krippendorff, 2004) to handle this scope, but as cluster statements are paraphrases capturing broad themes from multiple sources, some detail is inevitably lost in this process. Our findings, therefore, should not be viewed as fully inclusive of all specialized cases and arguments in the literature.

Constraints on the literature we sampled also limit the comprehensiveness of this study. For instance, we rely exclusively on journal articles and books for a meta-analysis of engineering practice. Consultation of literature from various additional realms such as trade magazines, blogs, and other nonpeer-reviewed sources could have increased our breadth of coverage across facets of engineering work but at the expense of accuracy and unbiasedness. Again, this consideration suggests our analysis is not fully comprehensive, prompting us to frame our findings as a series of propositions about prevalently discussed elements of engineering work rather than as a conclusive or complete characterization.

Our analysis of O*Net job description data in Search 4 carries limitations. Although we find four prominent occupational clusters among the results, less-definitive groupings of occupations may also exist as may lone occupations that do not fit neatly among the four clusters. Furthermore, O*Net itself does not claim to be an unabridged or global source of job descriptions. While several studies have found general applicability of O*Net data to varied non-US labor markets (Hanna et al., 2019, p. 606), further investigation is required to fully assess the applicability of our findings globally. We proceed assuming that the Search 4 results represent typical and prevalent examples of jobs in close proximity to engineering roles in our current time, but we do not assume that these results represent a comprehensive list of possible job titles meeting the search criteria.

4 | SYNTHESIS AND DISCUSSION

4.1 | Typology synthesis: Characterizing engineering students' occupational outcomes

Next, we develop a set of propositions supporting a typology of occupations' engineering relatedness. We begin by posing a *central assumption* to underlie the typology and its governing propositions: that any occupations appropriately characterized as "engineering" must involve some application of knowledge and skills from engineering domains, which we assume are represented at least in part by the knowledge and skills listed in accreditation criteria for baccalaureate engineering programs (e.g., ABET, 2019; refer also to signatories listed at International Engineering Alliance, 2014, p. 22). We make this assumption independent of whether the occupations require accredited engineering degrees as entry criteria (for a discussion on alternate educational pathways in engineering, refer to NAE, 2018). Furthermore, as knowledge and skills listed in engineering accreditation criteria can be applied to many types of occupations (Brunhaver et al., 2013; NAE, 2018), the propositions outlined next introduce increased specificity for categorizing occupations in terms of engineering relatedness beyond that which is implied by this assumption.

We establish our initial proposition based on the central finding of this study's systematic literature review:

Proposition 1. *A consensus or near-consensus unifying attribute of engineering occupational roles is an ascription of design responsibility upon the practitioners undertaking such roles.*

Allusions to engineering practitioners' design responsibility in historic literature (preceding our review) give us confidence in the enduringness of this proposition. Baddour et al. (1961), for example, describe engineers' "willingness to assume final responsibility for a useful result" (p. 650). Mann (1962) discusses engineers' "acceptance of responsibility for solutions" (p. 2), and Hall (1965) explains that "the engineer has the responsibility of … [ensuring] the product of [a] design can be achieved" (p. 294). We observe facets of design responsibility described as obligations of engineering practice over many decades leading to recent sources' similar conclusions.

Despite Proposition 1's seemingly basic assertion that design responsibility unifies engineering occupations, a more detailed review of the literature and of sample job descriptions makes it clear that such a criterion is not without complications. The following additional propositions address these complications.

First, the specific ways engineering practitioners uphold design responsibility is likely to change over the course of their careers. Literature describes a tendency for practitioners to take on increasingly managerial roles as they gain experience (e.g., Biddle & Roberts, 1994; Busby & Coeckelbergh, 2003; NAE, 2018; Rynes et al., 1988). In constructing this typology, we must ask: Should transitions from individual contributor engineering roles into management roles be characterized as cases of persistence in or departure from engineering occupations? Similar to cases of students' transitions into early-career roles, managerial transitions can also be assessed in terms of the new roles' proximity to design responsibility. Existing literature and a logical application of Proposition 1 in turn support categorizing certain managerial roles as engineering roles. Robinson (2012), for instance, discusses how many who take on "engineering manager" roles remain responsible for technical elements of work, while Trevelyan and Tilli (2007) conclude that "management is an intrinsic part of many engineering roles" (p. 302). If one considers engineering a distinct occupational function within organizations—one with its own internal hierarchy of functional oversight—then the engineering function itself can be considered holding design responsibility with its members as enactors of this responsibility at various levels of seniority and accountability. By this reasoning, if an individual engineer makes an error, the individual's direct-line manager holds responsibility for ensuring that the error is resolved just as the individual also holds responsibility. In a most direct exemplification of this arrangement, certain safety-critical engineering contexts employ an "engineer of record" to sign off on work conducted by comparatively junior engineers, reinforcing the notion that engineering chains of command can ultimately preside over design responsibility (Gillum, 2000; Kardon, 2005). Furthermore, those higher in the chain of command who delegate but still oversee and can sign off on engineering decisions can be considered to be carrying design responsibility. Yet one cannot assume that all roles that engineering practitioners acquire as they gain experience necessarily fall along this chain of responsibility: Individuals attaining managerial roles in other occupational functions such as in business development, strategy, or operations may effectively take on roles one or more degrees removed from design responsibility, positions less aptly categorized as "engineer" in the conventional sense. We summarize our conclusions about role progressions in relation to design responsibility through the following proposition.

Proposition 2. *The nature of design responsibility in engineering roles can take different forms in roles at early career stages compared to roles at advanced career stages.*

Proposition 2a. *Members of engineering occupations hold design responsibility over their own contributions although they may or may not (depending on experience levels and context) require a more experienced engineer or engineering manager to validate their contributions.*

Proposition 2b. *Certain members of engineering occupations in senior-level and managerial roles hold design responsibility over their own contributions as well as over their team's, department's, or directorate's contributions. Individuals who have delegated engineering design responsibility but are ultimately responsible for outcomes are still considered to be holding design responsibility.*

Figure 2 illustrates the partial typology constructed thus far. Here, we have instantiated two axes of the framework: one of proximity to design responsibility and one of increasing occupational seniority. The following additional propositions serve to incorporate further differentiating detail into the framework.

Next, we turn to the elaborative question: design responsibility over what? In other words, what is the specific scope that this responsibility covers? Clearly, there are others beyond engineers involved in product (or process, service, or system) development and sustainment even if we limit our consideration to contexts involving product parameters rooted in applied sciences or mathematics (i.e., work within conventional engineering domains). Other occupations' involvement is highlighted by the prevalence of documented roles entailing direct collaboration with engineers such as examples revealed by our Search 4: industrial designers who "prepare sketches," "[build] models," and "confer with engineering;" project managers who "lead and guide the work of technical staffs;" and many more (see Table 8).

Defining engineering work in the 21st century involves acknowledging the collaborative character of today's product and technology ecosystems while also acknowledging that engineers' responsibility is unique among occupations. The engineering ethicists' (and others') arguments that to take on an engineering role is to accept responsibility for the efficacy and safety of designs, be they newly created or sustained designs (see Tables 2 and 6), combined with a more granular definition of design itself help to elucidate this uniqueness. Scholars of engineering design have long defined

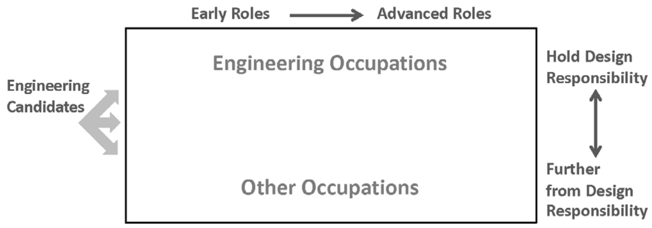

FIGURE 2 Partial construction of an engineering relatedness typology for occupations

design in terms of both form and function and have identified processes by which functional requirements (i.e., target functions) are embodied as specific implemented forms (i.e., realized forms with their consequent functions) (Cross, 2006; Pahl et al., 2007). When it comes to the functional specification of products—what a product should accomplish, the utility it should provide to its users, even the shape or appearance it should exude—our literature review makes clear that such decisions are collaborative endeavors today between those practicing engineering and those in complementary roles, be they designers, managers, strategists, or others. However, our review also indicates that governance of the implemented form of products, and particularly how given functionalities map to their enabling forms both initially and across a product's lifecycle, is a unique responsibility of engineers. The examples that follow help illustrate these complementary but differing natures of responsibility.

For engineered products (or processes, services, or systems), particularly complex ones, form is generally codified by revision-controlled sets of governing information artifacts—drawings, schematics, software source code, chemical formulations, etc.—and those practicing engineering take responsibility for the integrity of this formal product definition (initially and over time) whether by direct instantiation, by assessing others' work, or by contributing governing analyses that could prompt change or endorse sustainment (Table 6). Eckert et al. (2004), for example, describe a collaborative environment at an aerospace firm where members of various disciplines propose and review product changes in response to customer concerns while a senior engineer is ultimately responsible for the technical vetting and approval of alterations to a design baseline. Kardon (2005) describes scenarios in civil and structural engineering where engineers-of-record are formally liable for the performance of designs instantiated under their watch and can be charged with negligence if designs fail to perform as functionally specified. Twigg (1998) describes a complex supply chain in the automotive industry where control over design integrity is maintained through clear assignment of engineering design authority and sign-off responsibility. Following from our review (Tables 2 and 6), the stewardship of implemented design forms is a hallmark of what it means to be an engineer—acceptance of responsibility for the form-consequent efficacy and safety of what is deemed fit for use initially and over time—often as marked by sign-off duties in information management systems that control releases of or changes to products' defining or substantiating information.

A summative hypothetical example can be constructed from our findings: Consider a scenario where workplace colleagues collaborate on how a laptop computer should look and feel and how it should perform in a variety of technical areas. Inputs from a range of occupational roles may inform the conclusion that an aluminum case is most aesthetically appropriate for this laptop; yet when it comes to committing to the specific alloy(s) of aluminum acceptable for use from among essentially identical-looking alternatives while taking ownership of performance-related implications (e.g., heat transfer, structural integrity, and manufacturability, among others), this commitment becomes the engineer's unique responsibility. This responsibility for product form—pertaining to either the creation of new forms or sustainment of existing ones and extending from the smallest levels of definition (e.g., alloy composition in this scenario) to macroscopic levels—characterizes the design responsibility conventionally affixed to engineering roles.

Yet the way engineering roles are embedded in broader product and technology development ecosystems suggests engineers' work is often moderated by others. The well-documented presence of complementary roles indicates that practicing engineering rarely involves having free reign over product form. Industrial designers' inputs, for instance, may determine a product's net shape while project managers may establish constraints and objectives that impact engineers' decisions (Table 8). The broad set of pertinent 21st-century role descriptions suggests a give-and-take surrounding products' target functionalities, which we conceptualize as a collaborative responsibility shared between those practicing engineering and those in other roles that are closely coupled to engineering activity. We offer Proposition 3 to distinguish conventional engineering design responsibility from among the complementary responsibilities at play.

Proposition 3. *The nature of design responsibility in engineering roles differs in how it pertains to the* form *of designs versus the* function *of designs.*

Proposition 3a. *Those occupying engineering roles hold* determinate responsibility *for instantiating or governing the* form *of designs and for form-consequent function emerging from this form.*

Proposition 3b. *Those occupying engineering roles share* collaborative responsibility *with those in other related occupations over th*e target function *of designs.*

We use the term "governing" within Proposition 3a in reference to contexts of ongoing determinate responsibility over design forms (e.g., monitoring and updating in-service designs, analyzing failures and implementing corrective

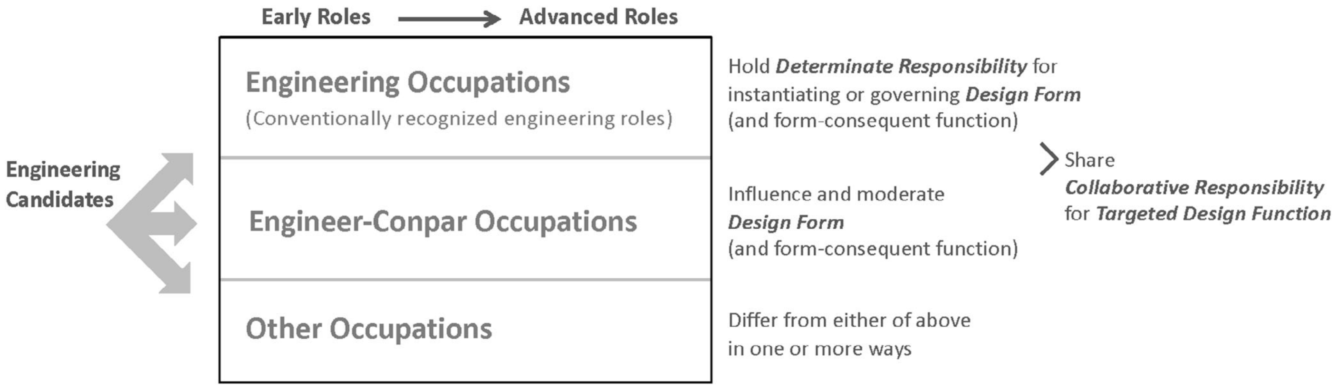

FIGURE 3 Further development of an engineering relatedness typology for occupations

actions, etc.) at various product lifecycle stages beyond initial design instantiation (see Table 6). Meanwhile, Proposition 3 prompts an expansion of the typology from its basic skeleton (Figure 2) to accommodate this more granular distinction of design responsibilities among occupation types. An intermediate occupation type is introduced as shown in Figure 3. This expansion presents a need to establish categorical names, a delicate task given our imperative for neutral category labels.

We opt for English–Latin hybrid category names in pursuit of neutrality. As with labeling choices in certain scientific fields, use of Latin-based categorization takes advantage of the diminished emotional anchoring associated with a legacy language, allowing us to uniquely establish the category names without their being laden with prejudicial meaning. We introduce the following terms:

- ***Engineer-Agnita occupations*** (or per convention and hereafter ***Engineering occupations***)—historically recognized or conventionally acknowledged occupations of engineers. (The hybrid name utilizes the Latin "agnita" meaning recognized or acknowledged).
- ***Engineer-Conpar occupations*** (abbreviated as ***Engineer-C occupations***)—engineering partners and colleagues; fellow participants in product or technology development. (The hybrid name utilizes the Latin "conpar" meaning companion, mate, or partner).

The scheme in Figure 3 illustrates the complementary, interdependent nature of the roles that engineers and engineer-Cs play in the product or technology development realms.

We proceed to characterize *collaborative responsibility for targeted design function* and to establish defining criteria for engineer-C roles. Our review suggests a relationship between engineer and engineer-C occupations that is distinctly close compared to that between conventionally recognized engineering occupations and other occupations. Sources provide several examples of this proximity:

- Sheard (1996) describes system analysts' role to "confirm that the designed system will meet requirements," (p. 2) inclusive of conducting modeling to assess design performance.
- Kemper and Sanders (2001) describe an interplay between engineers and industrial designers whereby stylistic and usability attributes of designs are shaped by the latter.
- Van de Weerd et al. (2006) illustrate product managers' role in establishing product requirements based on customer needs and parsing these requirements into specific planned product releases.
- Rauniar et al. (2008) discuss product managers' role in setting goals and targets for product development teams that are in "strategic alignment" with business and company goals.
- Onarheim (2012) describes project managers' responsibility for translating target product profiles into project constraints through a process of establishing "corner flags."

The above analyst, designer, product manager, and project manager portrayals illustrate design form-moderating roles that are characteristic of engineer-Cs in our framework. In each of these cases, we see how the work of these

TABLE 9 Characteristics of the categories of design responsibility

Markers of *Collaborative Responsibility* for target design function
Individual belongs to an occupation that
– Plays a direct role in establishing the target functional specifications of products
– Provides information directly to those tasked with instantiating (or maintaining) the design form of products in order to influence products' form
– Reviews and influences proposals for new product designs or changes to existing product designs
– Monitors, simulates, or analyzes a product's performance to establish feedback on how well it is performing, and relays this feedback to those tasked with instantiating (or maintaining) the design form of the product
– Conveys information about product issues or failures directly to those tasked with correcting the instantiated form of the product
– Creates communication artifacts or documents that explain, discuss, or clarify technical information about a product by working directly with those tasked with instantiating (or maintaining) the design form of the product
Markers of *Determinate Responsibility* for instantiating or governing design form
Individual belongs to an occupation that
– Holds responsibility for establishing, maintaining, or adapting the specific defining details of a product or part of a product, and is ultimately accountable for the correctness and integrity of these details
– "Signs off" as the technical authority certifying the effectiveness and safety of a design, or on behalf of a particular technical function involved in certifying the effectiveness and safety of a design
– Should there be a product flaw discovered, is responsible for establishing conclusions about the cause of the flaw, and for establishing and implementing the specific change that will resolve or mitigate the flaw

Note: In the case of either category above, affirmation of any one or more of the markers indicates possession of the associated responsibility type. Here, the term "products" refers to products, processes, services, or systems.

individuals is closely coupled to the work of engineers who presumably act upon and are guided by the outputs of such engineer-Cs.

Furthermore, the typology distinguishes other occupations from both engineers and engineer-Cs in that others do not directly share collaborative responsibility for target product function nor do they directly influence, moderate, instantiate, or sustain product form (i.e., their roles are not "closely coupled" to conventionally designated engineering roles). For instance, consider the possible difference between an engineer-C (who is a project manager) and a financial analyst. Although the two may reside in the same organization, the financial analyst is likely further removed from design responsibility. The financial analyst may determine cost targets for a particular product line or business; this determination may then shape project-specific cost targets which, in turn, may translate into constraints upon design form. However, while the project manager is likely to directly interface with engineering to control these costs and translate them into design-influencing parameters, the financial analyst is more likely to influence design form through intermediaries (such as the project manager) rather than directly.

The characteristics of jobs within the four engineering "nearest neighbor" occupational clusters from Search 4 combined with detailed role descriptions from the literature (e.g., Onarheim, 2012; Rauniar et al., 2008; Sheard, 1996; Van De Weerd et al., 2006) suggest possible modes of collaborative responsibility shared between conventionally recognized engineers and those in engineer-C roles. We present a series of expected markers of *collaborative responsibility over target design function* in Table 9 alongside markers of *determinate responsibility over design form* based on our review (i.e., from Table 6 and Propositions 1–3). The characteristics in Table 9 can inform the construction of research survey questions used to ascertain individuals' job responsibilities and, in turn, their jobs' categorization as engineer or engineer-C. It is important to note that the statements in Table 9 assume that such responsibilities are held at the occupational function level (e.g., at a given instant, an individual need not be engaged in any of the activities in Table 9 in order for the individual's occupation to be categorized as engineer or engineer-C). Affirmation of any one of the given responsibility statements in Table 9 indicates responsibility at the associated categorical level (i.e., collaborative-over-function or determinate-over-form). Table 9 does not constitute an exhaustive list but serves to generally characterize these two responsibility categories based on the literature review.

Proposition 4 formalizes the conceptualization of engineer-C occupations. Proposition 5 elaborates on what distinguishes other occupations from engineers and engineer-Cs.

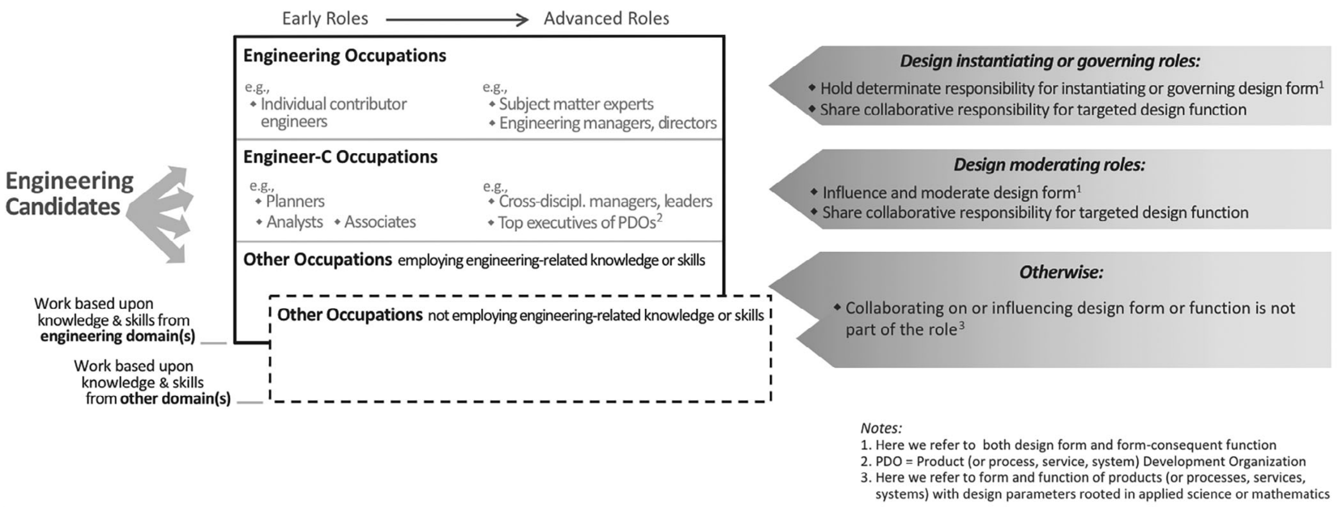

FIGURE 4 Typology for categorizing occupations in terms of engineering relatedness

Proposition 4. Engineer-Conpar *(engineer-C) occupations share* collaborative responsibility over the target function *of designs with engineering occupations and influence and moderate the* form *of designs (and the form-consequent function of designs).*

Proposition 5. *Other occupations (i.e., neither engineers nor engineer-Cs) do not share collaborative responsibility over the function of designs and do not directly influence or moderate the form of designs.*

Proposition 5a. *Some from among other occupations employ knowledge and skills from engineering domains (i.e., knowledge and skills listed in accreditation criteria for baccalaureate engineering programs) in their work and can be categorized as* Other occupations employing engineering-related knowledge and skills (*or* Other engineering-related occupations).

Proposition 5b. *Some from among other occupations do not substantively employ knowledge and skills from engineering domains in their work and can be categorized as* Other occupations not employing engineering-related knowledge and skills.

Propositions 5a and 5b differentiate among other occupations that are neither categorizable as engineer nor engineer-C. As follows from the central assumption expressed at the start of this section, we assume that all engineer and engineer-C roles involve at least some application of knowledge and skills from among those listed in engineering baccalaureate program accreditation criteria. However, it is likely that a subset of other individuals also employ such knowledge and skills in roles beyond those meeting the criteria for the engineer or engineer-C designation (NAE, 2018; refer also to Brunhaver et al., 2013). As discussed by the NAE (2018, p. 37), past studies have used measures of either respondents' self-assessment of their work's relatedness to their engineering degree or of employers' job education criteria to assess the applicability of engineering degree-related knowledge and skills at particular jobs. Such approaches can be used to apply Propositions 5a and 5b (following the application of the prior propositions) to categorize roles using this typology.

Full instantiation of the typology based on Propositions 1–5 is shown in Figure 4. A third axis has been added to earlier renditions of the typology—one that delineates the knowledge and skill domains upon which work is primarily based. Note that the typology suggests engineering relatedness of occupation types by cells' physical distance from the "engineering occupations" category. The dashed line surrounding "other occupations not employing engineering-related knowledge or skills" indicates that this category is not specifically bounded other than by its distinction from the remaining three categories. The bullet points within the upper cells of Figure 4 illustrate how job scope, expertise level, and managerial purview may vary within the bounds of those occupational categories; however, this guiding text is not intended to denote specific job titles. The typology avoids utilizing job titles as a means of categorization due to potential variation in titles' meaning across employers. The typology, therefore, best serves as a tool for original research when individuals' job responsibilities can be assessed through surveying or interviewing rather than as a scheme for parsing existing job titles into categories. In the remaining sections of this article, we discuss employing the typology in original research, the typology's limitations, and opportunities for further development.

4.2 | Employing the typology

The example jobs uncovered in Search 4 (refer to Table 8)—nonengineering-titled roles in close proximity to conventional engineering roles—provide pertinent cases for exploring this new categorization approach. O*Net's data on each of these roles, meanwhile, provides us with enough information to discuss possible categorization rationales for the sake of methodological illustration.

Take, for instance, "Software Application Developers" as listed in Table 8—setting aside for a moment debates on whether individuals in these roles should be eligible to acquire professional licensure as engineers (Thornton, 2012). The "Software Application Developer" profile includes language such as: "develop, create, and modify general computer applications software," "may supervise computer programmers," "modify existing software to correct errors or to improve performance," and "design, develop, and modify software systems using scientific analysis and mathematical models … to predict and measure outcomes and consequences of design." This language tells us about factors pertinent to our framework: that the role extends beyond computer programming to include purview over design outcomes, performance validation, and correction of errors affecting performance. This role, thus, appears to carry markers of *determinate responsibility over design form* per Table 9. In addition, the job profile states that the individual will "analyze user needs and requirements" and "confer with systems analysts, engineers, programmers, and others to design systems," job features reflecting *collaborative responsibility over target design function* from Table 9. Ideally, survey or interview data from this role's occupant would bolster these conclusions, but from the evidence we have, the role appears consistent with that of an engineer based on the typology. We cannot, however, generalize that all "software developer" roles align with the engineer criteria nor can we draw such a conclusion about the many other software-related roles in today's job market based on this one example.

Next, we consider the "Project Manager" profile from Table 8, which includes such language as "plan, initiate, and manage projects," "lead and guide the work of technical staffs," "serve as liaison between business and technical aspects of projects," and "confer with project personnel to identify and resolve problems." Throughout the profile, we see indications of *collaborative responsibility over target design function* but no such language implying *determinate responsibility over design form*. This profile, thus, suggests a role consistent with an engineer-C occupation. Yet we cannot conclude that all project managers are engineer-Cs; role variants may exist where project managers also possess responsibility over design form (Allen & Katz, 1995) and could be considered engineers. Again, details about individuals' specific job responsibilities are needed to reach the most robust conclusions about occupational categorization using the typology.

Analyses similar to these can be carried out for any of the types of jobs listed in Table 8 and beyond, from "interface designers" to "product development managers" to "systems analysts." Some cases are more nuanced than others; for example, those with "designer" in their titles undoubtedly carry some type of responsibility for "design"—yet here, we return to our discussion on what "design" encompasses for purposes of this typology: It is not simply what a product looks like nor its list of performance requirements; rather, it is an item's codified form that maps to its consequent efficacy and safety. Those in engineering roles are "on the hook" for outcomes tied to the lowest levels of design form detail (whether they delegate tasks tied to this detail, whether they instantiate the detail themselves, or whether they monitor and sustain the forms of existing designs); such is the essence of *determinate responsibility over design form*.

4.3 | Challenging cases and typology limitations

Cautious that extensive categorization rules could become unwieldy, we sought to balance the simplicity of the typology with its maximal accommodation of engineering students' possible occupational outcomes. As a result of this balance, however, we expect that some number of occupations will pose categorization challenges.

Engineering faculty roles create one such dilemma: Are engineering professorships or instructorships themselves engineering roles? On the one hand, faculty educate future engineers and are engineering domain experts. *Determinate responsibility over design form*, however, may be limited in faculty roles due to research and teaching obligations restricting opportunities to take full ownership of the design form details of deliverable products, processes, services, or systems. Yet faculty roles are not categorized effectively by the typology's other designations either. These roles present one case where we simply suggest employing additional categorization. Uniquely classifying individuals' occupational outcomes in engineering faculty roles in their own category (i.e., distinct from the four primary categories of this framework) provides transparency and allows the users of results to further interpret or process the findings as needed.

Technical consultant roles pose another challenging case; however, these roles can typically be parsed into one of two categories depending on the roles' inherent responsibilities. For example, consultant roles in civil, structural, geotechnical, or environmental engineering disciplines, among others, may involve determinate responsibility over instantiated designs in cases where practitioners supply, approve, or vet finalized designs or design-enabling substantiation to projects while they (or a superior or their firm) are affixed to the projects as "engineers of record." In other cases, however, individuals may hold the title of "consultant" in seemingly engineering-related contexts but not possess determinate responsibility over instantiated design forms. Such may be the case when consultants provide various forms of nonbinding studies or recommendations to engineering teams. These latter roles are presumably better characterized as engineer-Cs.

The field of systems engineering also poses a challenge to this categorization framework. The International Council on Systems Engineering (INCOSE) defines systems engineering broadly:

> Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods (INCOSE, 2019).

At first glance, this general definition does not appear to imply *determinate responsibility over instantiated design form*, suggesting systems engineering roles may not align with a conventional "engineer" categorization. Closer consideration of the discipline's published "areas of focus" (INCOSE, 2019) suggests that "design synthesis" and "system verification and validation" components of roles can potentially involve responsibility for realized form and form-consequent function of systems. While design responsibilities in systems engineering may be at a higher level of abstraction (e.g., at the "architectural" level) compared to those of other engineering roles, some such roles may involve directing the detailed manifestation of designs such as through design validation efforts that drive the instantiated design form. Sheard's (1996) "twelve systems engineering roles," meanwhile, describes a pronounced diversity of what may be considered systems engineering; here, we see analysts, designers, managers, and coordinators among others. It is plausible that some systems engineering roles are better described as engineering roles while others are better described as engineer-C roles.

4.4 | Future work

Various next steps can further validate the typology, facilitate its continued evolution, and enhance its usability for researchers. First, the tangible markers of design responsibility (i.e., Table 9) can be further substantiated through field validation. This field research would assess the degree of corroboration between these markers and practitioners' and their managers' acknowledgement of the underlying responsibilities, resulting in potential refinement to Table 9. Sampling for such studies would be of chief concern. The present set of markers was derived from commonalities across an intentionally broad set of engineering practice literature. While we should scour practice contexts for substantive evidence prompting refinement to the list, we should avoid major revisions or additions drawn from niche contexts.

As we and the research community revisit Table 9, it will be important to account for certain limitations (introduced earlier in this article in *Purpose and Criteria for an Engineering Students' Occupational Outcomes Typology*) tied to the construction of this table. The criteria listed in Table 9 were distilled from a set of existing literature spanning many years in order to maximize the criteria's recognizability among key stakeholders; yet while this literature set is bounded in time, engineering practice continues into the future. Moreover, beyond the prominent themes drawn from this literature to shape the typology, this literature also captures ongoing debates that surely had not reached their conclusions at the time our search window closed (such as the more recent debates about engineers' professional unity among sources listed in Table 2). Some of these debates pertain to the scope or extent of "design responsibility": how far, for instance, does design responsibility extend beyond the immediate "safety and efficacy" experienced by products' users? Sources listed in "Discussion on societal and occupational expectations of engineers" in Table 2 grapple with this question, making cases for social, community, and global applications of this responsibility. We highlight that the current study presents design responsibility as a foundational, or even minimal, theme that lends itself given its broad definition to further refinement and expansion in step with contemporary consensuses. This study, therefore, invites follow-on research to characterize the application of engineers' design responsibility to areas of, for example, social justice, human rights, and the environment, potentially producing augmentation to the basic criteria listed in Table 9.

Next, evaluating the typology's degree of coverage is prudent. For this framework to be useful to the research community, a high percentage of engineering graduates' occupations must be categorizable in it. Initial attempts at employing the typology for engineering schools' alumni surveys, for example, can serve as opportunities to both develop and validate survey questions and to understand reasons for any coverage issues. Such typology use assessments along with broader feedback from the research community could prompt refinement of the typology to increase coverage, but the benefits of any added categorization rules must be weighed against the usability benefits of a parsimonious framework.

In the typology's present state, its knowledge and skills domain axis remains incompletely defined. For instance, we rely on lists of knowledge and skills within engineering baccalaureate program accreditation criteria (refer to *Typology Synthesis*) to define a position on that axis that accommodates engineer, engineer-C, and other engineering-related occupations but we do not define additional axis positions. A follow-on systematic review to establish other key knowledge and skill domains could make the typology more capable of meaningfully categorizing occupations from a diverse array of possibilities. As follows, the typology could then apply the concept of design responsibility as a roles delineator separately to varied domains (allowing engineering roles to be reliably categorized, for example, alongside roles with design responsibility in culinary, media, fashion, theater, etc.). With such an expansion, the typology could better accommodate differing occupational outcomes marked by responsibility over the forms of "things" including those beyond conventional boundaries of engineering.

5 | CONCLUSIONS

Adoption of an occupational outcomes typology that acknowledges a range of engineering relatedness among occupations has the potential to enhance clarity and consistency in future engineering education research. Recent studies indicate substantive proportions of engineering graduates undertaking occupations that defy conventional categorization in engineering. In the United States, for instance, the Census Bureau (2014) indicates that 38% of these graduates have acquired computer-, managerial-, or business-related roles deemed "non-engineering" while the NAE (2018) estimates that 45% of graduates have undertaken roles in close proximity to engineering but not conventionally labeled as such. Legacy national-level occupational measurement systems make it quite difficult to know the true nature of the work undertaken by these individuals; some likely remain closer to engineering than others. This study suggests a categorization scheme that distinguishes between engineering occupations, occupations closely coupled to engineering ("engineer-Cs"), other occupations employing engineering-related knowledge and skills, and occupations that do not substantively involve engineering-related knowledge and skills. Furthermore, engineering faculty roles are proposed as their own distinct category. Shared adoption of a more granular categorization scheme such as that presented here offers a way for the engineering education research community to unify its occupational outcomes measurement while enhancing one another's understanding of empirical results. Adoption of this scheme may also enable educators to better illustrate key differences among seemingly similar engineering-related career options that students now face.

5.1 | The rise of the engineer-Cs

The 21st century brings evidence that the number of individuals engaged in engineer-C work may be growing rapidly; for instance, the United States saw its largest project management professional association's (the Project Management Institute's) membership quadruple between 1999 and 2005 (DiVincenzo, 2006) while more recent reports cite a sustainment of similar growth trends globally (Farashah et al., 2019). Engineering educators face a choice of whether to better track the numbers of engineering graduates undertaking these types of roles and, consequently, to decide whether engineering education should address student preparedness for such roles. The latter question is beyond the scope of this article, but measurement of graduates' participation in engineer-C roles could help prepare educators to answer it in the near future.

Furthermore, measuring occupational outcomes with the increased granularity afforded by this typology can support efforts aimed at enhancing diversity and equality in the engineering workforce. If participation in engineering work is measured in a binary fashion (e.g., work either is or is not deemed "engineering"), then we learn less about underrepresented groups' occupational outcomes that diverge from conventional categorization. Studies suggest that understanding gender inequality in engineering practice, for instance, could benefit from a more precise measurement of these outcomes. Cech (2013) found evidence of gendered trends in participation across engineering-related roles, with men exhibiting proportionally greater representation in conventionally recognized engineering roles and with women's representation greater in roles with comparatively increased social, administrative, or managerial components. Seron et al. (2016) observed similar role segregation in engineering students' project teams, with women tending more toward project management duties relative to men. Granular data on underrepresented groups' participation across engineering-related role types, including role types inconsistently classified in the past, may help researchers better understand underrepresentation through more precise analyses of persistence in (or departure from) engineering careers.

5.2 | Learning from engineering's past and present, preparing for the future

Williams (2002), Downey (2005), the NAE (2018), and others contend that technological work is changing rapidly in the 21st century and that an ever-broadening array of occupations will routinely engage with technology and play roles in its development. As engineering students take on increasing varieties of roles, educators will face choices about how their academic institutions view and deal with this occupational dispersion. Keeping pace with ever-changing sets of job titles in real time may be impossible. Yet the literature on engineering work suggests an enduring and unifying theme about what it has meant to be an engineer: *design responsibility*—responsibility for products' (or processes', services', or systems') efficacy and safety through governance of designed forms. Although we cannot predict the future, monitoring engineering students' occupational outcomes in relation to a common theme—even as new areas of technology come and go—may serve an important benchmarking function, revealing how workforce roles and participation patterns are evolving and whether this occupational dispersion is equitable.

Amid the recent push to clarify the meaning of engineering work, scholars of engineering education have built a compelling case that educators should include social, coordinative, and collaborative job characteristics in their core conceptions of engineering practice (e.g., Bucciarelli, 2002; Stevens et al., 2015; Trevelyan, 2007, 2010). These researchers emphasize that coordination and collaboration are central parts of engineering and not merely peripheral job attributes nor necessarily evidence of new hybrid roles. We must underscore this typology's compatibility with these notions. The typology not only highlights that conventionally designated engineering roles rest upon key collaborative responsibilities but also that engineers are unique in their simultaneous possession of specific responsibility for the efficacy and safety of designed forms.

It is difficult to know if today's engineering candidates understand this responsibility-based distinction between engineering, engineering-coupled, and other types of work. Students are no doubt exposed to a complex array of informal messages about engineer-C roles via social media and the popular press, for instance, characterizations of product managers as "the digital industry's rock stars" (Tsuchiyama, 2011). The categorization scheme presented in this study renews a focus on a responsibility-based conception of engineering, which in turn invites an exploration of learning goals underlying what it means to uphold design responsibility that could be better represented in curricula. Furthermore, if the engineering education community embraces the aggregate scope of supporting career preparedness for both engineering and engineer-C roles, attention could be paid to illustrating to students the unique facets of responsibility ascribed to these complementary groups in engineering practice. The responsibility-based conception of engineering more generally can help educators preemptively prepare students for working with new technologies whose technical underpinnings may not yet be codified into curricula but toward which the foundational concepts of design responsibility can nonetheless be applied.

In these changing times and as educators work to increase participation of underrepresented groups in engineering occupations, much remains to be examined in whether these groups' inclusion is growing in conventional engineering roles, whether growth is largely in engineer-C or other engineering-related roles, or whether growth occurs across categories. We aim not to negatively judge students' pursuit of nonconventional roles in proximity to engineering; in fact, enhancing engineering education's preparation of individuals for these roles may be prudent. Yet our findings suggest that career pathway studies can achieve greater accuracy and transparency through the use of a stratified typology for engineering relatedness of occupations. Through this approach, we can meaningfully assess progress toward achieving equitable participation in engineering work among all aspiring engineers.

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