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The evolution of mathematics education for engineering students: A literature review

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ABSTRACT

Over the past six decades, undergraduate mathematics education for engineering students has undergone a significant and multifaceted transformation, driven by technological advances in digital computing, evolving institutional accreditation frameworks, pedagogical reform movements, and disciplinary shifts toward data-intensive and computational methods. This literature review synthesizes influential scholarship spanning 1948 to 2025, tracing the evolution from traditional calculus-based instructional sequences to contemporary curricula that are integrated, computation-rich, and application-oriented. Five major transitions are identified: the formalization of mathematics as a service discipline (1960s–1970s), the calculus reform movement and early computational integration (1980s–1990s), accreditation-driven curricular flexibility (1990s–2000s), diversification beyond calculus toward statistics, linear algebra, and numerical methods (2000s–2010s), and the emergence of data science and AI-informed mathematics education (2020s). Despite substantial progress, significant gaps persist in longitudinal multi-institution studies, rigorous empirical outcome assessment, and systematic understanding of the barriers to implementation. This review concludes by identifying directions for future empirical research that can more comprehensively evaluate the effectiveness and sustainability of engineering mathematics curricula.

Keywords: mathematics, engineering, education, challenges

INTRODUCTION

Engineering education has undergone profound changes since the mid-twentieth century, yet few aspects of the undergraduate curriculum have evolved as substantially—or as contentiously—as mathematics instruction. What began as a relatively standardized sequence of calculus, differential equations, and applied analysis has diversified into a complex and dynamic landscape encompassing linear algebra, numerical methods, statistics, optimization, computational modeling, and, increasingly, data science. This transformation reflects not merely pedagogical innovation but fundamental shifts in what it means to practice engineering in an era of ubiquitous computing, massive data generation, and artificial intelligence (National Academy of Engineering, 2004; Vest, 2008). The mathematical demands of contemporary engineering practice have outpaced the curricula designed for an earlier technological era, creating an urgent imperative for curricular reform (Grizzle, 2025; Pepin et al., 2021).

Despite these widespread changes, comprehensive longitudinal studies that examine mathematics curricula across multiple institutions, decades, and engineering disciplines remain surprisingly rare. The existing literature consists primarily of case studies from individual institutions, theoretical reflections on pedagogical approaches, historical narratives of specific reform movements, and recent empirical work on student learning outcomes. While each of these contributions is valuable in its own right, together they offer only fragmented views of a six-decade evolution that has reshaped how hundreds of thousands of engineering students encounter mathematics (Seymour & Hunter, 2019). The absence of a unified, evidence-based account of this transformation represents a significant gap in engineering education scholarship (Froyd et al., 2012).

This review addresses that gap by synthesizing the most relevant and influential publications from 1948 to 2025, with particular emphasis on works that: (a) discuss curriculum design, policy, and institutional change; (b) analyze pedagogical approaches and student learning outcomes; or (c) reflect on the evolving role of mathematics in engineering professional formation (Alpers et al., 2013; Winkelman, 2009). The review proceeds roughly chronologically, identifying major transitions, persistent tensions, and emerging directions. Ultimately, this synthesis aims to provide both a comprehensive historical account and a rigorous foundation for future systematic research on the structure, content, and effectiveness of engineering mathematics curricula.

Scope and Definitions

For the purposes of this review, “mathematics for engineering” encompasses service courses (calculus, linear algebra, differential equations, statistics), specialized methods courses (numerical analysis, optimization, computational methods), and integrated or embedded mathematics (mathematical content taught within or alongside engineering coursework). This review focuses primarily on North American contexts, particularly the United States, though it incorporates relevant international perspectives where available. The chronological organization spans roughly from the 1960s through 2025, though the distribution of sources is uneven, with substantially more literature available from recent decades.

METHODOLOGY

Search Strategy and Source Selection

This literature review follows a systematic and transparent approach to source identification, selection, and synthesis, consistent with established protocols for integrative reviews in education research (Torraco, 2005; Whittemore & Knafl, 2005). The review aims to be comprehensive rather than exhaustive: rather than attempting to include every published item touching on engineering mathematics education, it prioritizes influential, methodologically rigorous, and historically significant works that illuminate the major transitions, debates, and outcomes that have shaped the field over six decades.

The primary search was conducted across six academic databases: ERIC (Education Resources Information Center), Scopus, Web of Science, ACM Digital Library, IEEE Xplore, and Google Scholar. These databases were selected for their complementary coverage of engineering education, mathematics education, and higher education research. Supplementary searches were conducted within the ASEE (American Society for Engineering Education) proceedings archive, a primary venue for empirical and practitioner-oriented research in engineering education (Froyd et al., 2012). Reference lists of key review articles — particularly Pepin et al. (2021), Li and Chen (2024), and Kiianovska et al. (2018) — were mined to identify additional relevant sources through backward citation tracing.

Search terms were organized into three conceptual clusters, combined using Boolean operators. The first cluster addressed the subject population and context: “engineering students,” “engineering education,” “STEM education,” and “undergraduate education.” The second cluster targeted the curricular and content domain: “mathematics curriculum,” “calculus instruction,” “linear algebra,” “differential equations,” “numerical methods,” “computational mathematics,” and “data science education.” The third cluster captured reform, pedagogy, and outcomes: “curriculum reform,” “active learning,” “pedagogical innovation,” “student outcomes,” “accreditation,” and “mathematics misconceptions.” The searches were conducted in English and encompassed publications from 1948 through March 2025.

Inclusion and Exclusion Criteria

Sources were included in the review if they met the following criteria: (a) the primary focus concerned mathematics instruction, curriculum, or student mathematical learning within engineering or closely related applied science and technology programs; (b) the work addressed undergraduate (tertiary) education rather than exclusively K-12 or graduate-level contexts; (c) the source was published in a peer-reviewed journal, edited scholarly volume, or refereed conference proceedings, or constituted a widely cited institutional or policy report with clear methodological transparency; and (d) the work made a substantive contribution to at least one of the review’s focal themes: curriculum content and structure, pedagogical approaches, student outcomes, accreditation and policy, computational integration, or emerging topics in data science and AI. In line with the methodological recommendations of Grant and Booth (2009) for mixed-method integrative reviews, both empirical studies and theoretically or historically oriented scholarship were considered eligible, provided they offered substantive argumentation grounded in evidence or documented practice.

Sources were excluded if they focused exclusively on K-12 mathematics education with no relevance to the secondary-tertiary transition; addressed graduate or doctoral mathematics training without reference to undergraduate preparation; reported on mathematics education in contexts (e.g., pure mathematics programs, medical or law schools) without demonstrated applicability to engineering education; or were duplicated across databases. Conference papers of fewer than four pages and without substantive findings or arguments were also excluded. The resulting corpus was assessed for quality using a tiered framework: peer-reviewed journal articles and books were weighted most heavily; conference proceedings were included selectively based on citation impact and methodological rigor; and grey literature (working papers, preprints) was included only when it represented highly influential or recent work with no published equivalent.

Synthesis Approach

Following source selection, the included literature was organized thematically and chronologically through an iterative coding process consistent with narrative synthesis methodology (Popay et al., 2006). An initial reading of each source generated descriptive codes capturing the study’s context, primary argument, methodology, and main findings. These codes were then aggregated into higher-order thematic categories corresponding to the major transitions identified in the abstract: mathematics as a service discipline; calculus reform and computational integration; accreditation-driven flexibility; content diversification; digital pedagogy; and emerging data science and AI themes. Persistent challenges — student preparation, transfer difficulties, epistemological tensions, and implementation barriers — emerged as a cross-cutting thematic category not reducible to any single historical period.

The chronological organization of the review reflects both the developmental logic of the field and the temporal distribution of the available literature. As noted in the scope section, sources from earlier decades are substantially fewer and often retrospective in character, whereas the 2010s and 2020s are represented by a richer and more methodologically diverse body of work. This uneven distribution is itself a finding of the review: the field's capacity for empirical self-examination has grown considerably, even as longitudinal and multi-institutional perspectives remain underdeveloped (Froyd et al., 2012; Seymour & Hunter, 2019). Where meta-analyses or systematic reviews were available (e.g., Freeman et al., 2014; Li & Chen, 2024), these were treated as primary synthesis sources and weighted accordingly. The total number of sources included in the final review is 100, spanning theoretical, empirical, historical, and policy-oriented contributions from 1948 to 2025.

HISTORICAL FOUNDATIONS: EARLY ENGINEERING EDUCATION TO MID-20TH CENTURY

The Emergence of Formal Engineering Education

Engineering education in the United States traces its institutional origins to the land-grant colleges established under the Morrill Acts of 1862 and 1890. These institutions fundamentally democratized access to technical education, establishing programs that sought to balance practical, trade-oriented skills with theoretical foundations in mathematics and the natural sciences (Martin, 2023). Early curricula placed considerable emphasis on hands-on training in workshops, drafting, and surveying, with mathematics typically limited to algebra, trigonometry, and elementary calculus (Grayson, 1993; Reynolds, 1991) applied primarily to problems in mechanics and design. The mathematical component of engineering education at this stage was largely instrumental—valued for its utility in solving discrete practical problems rather than as a foundation for broader scientific reasoning (Cardella, 2008).

As engineering professionalized through the late nineteenth and early twentieth centuries, institutional actors—particularly the American Society for Engineering Education (ASEE) and the precursors to the Accreditation Board for Engineering and Technology (ABET)—began advocating for more standardized curricula that would legitimate the field as a scientific profession. The National Academies' historical analysis of engineering technology education documents that this period was marked by increasing tension between practitioners who favored shop-floor experience and academics who championed theoretical, science-based instruction (National Academies of Sciences, Engineering, and Medicine, 2017). Mathematics stood at the center of this debate: was it merely a tool for practical calculation, or a fundamental language for understanding and advancing engineering principles? This unresolved tension would recur throughout the decades that followed, albeit in different institutional forms and with different stakes.

Post-War Transformation and the Rise of Applied Mathematics

World War II and the subsequent Cold War dramatically accelerated the mathematization of engineering education and practice. The demands of radar system design, ballistics calculations, nuclear engineering, and early digital computing required engineers with levels of mathematical sophistication far exceeding what traditional mechanics-based curricula could provide. Federal investment in defense-related research and development created both the demand for mathematically trained engineers and the institutional resources to reform curricula accordingly (Geiger, 1993; Servos, 1980). By the 1950s, major engineering programs across the country had established robust foundational sequences in calculus, differential equations, and applied analysis as prerequisites for advanced coursework in virtually every engineering sub-discipline.

This transformation is vividly exemplified by the influential mid-century textbooks that defined engineering mathematics for an entire generation of students and instructors. Francis B. Hildebrand's trilogy—"Advanced Calculus for Engineers" (1948), "Methods of Applied Mathematics" (1952), and "Introduction to Numerical Analysis" (1956, revised 1987)—became foundational staples across engineering programs nationwide (Hildebrand, 1948, 1952, 1956). These texts articulated a critical conceptual shift: mathematics for engineers was not simply a diluted version of pure mathematics, but rather a distinct and rigorous discipline emphasizing applied analysis, approximation methods, and numerical techniques specifically adapted to engineering problems. Hildebrand's sustained attention to numerical methods proved particularly prescient, foreshadowing the computational revolution that would fundamentally transform both engineering practice and mathematics pedagogy within two decades.

By the 1960s, most accredited engineering programs required a standard sequence: calculus I-III (single and multivariable), differential equations, and often linear algebra or advanced engineering mathematics. However, these curricula remained largely localized, with individual departments exercising considerable control over content, pedagogy, and sequencing. The stage was set for the systematic reforms that would emerge in subsequent decades.

MATHEMATICS AS SERVICE DISCIPLINE: CROSS-DISCIPLINARY REFLECTION (1970s-1980s)

Reconceptualizing the Role of Mathematics

The 1970s and 1980s witnessed a growing critical reflection on the role of mathematics in engineering education, driven in large part by accumulating evidence of significant disconnects between how mathematics was taught in universities and how engineers actually employed mathematical tools in professional practice. A landmark investigation, reported in Mustoe and Lawson (2002) and drawing on empirical research conducted through the 1980s, systematically examined how mathematics functions in engineering workplaces and surveyed both engineering faculty and graduates about the adequacy of their mathematical preparation. The findings substantially challenged prevailing curricular assumptions: effective workplace engineering demanded primarily mathematical modeling, approximation, numerical computation, and the interpretation of results within physical contexts—not the symbolic manipulation or formal proof that dominated traditional university instruction. These empirical findings lent urgency and legitimacy to calls for curricular reform that had previously been largely theoretical (Alpers, 2010; Noss, 1994).

This body of research suggested that the traditional mathematics curriculum—designed largely by and for mathematicians—consistently failed to cultivate the mathematical habits of mind most essential for engineering: the capacity to translate physical problems into tractable mathematical formulations, to assess the validity and limitations of solutions, to manage uncertainty and approximation judiciously, and to leverage emerging computational tools effectively. These insights catalyzed a broader and consequential reconceptualization of engineering mathematics: rather than functioning as a prerequisite hurdle to be cleared before "real" engineering could begin, mathematics came to be understood as an integral and ongoing component of engineering thinking, design reasoning, and professional identity (Gainsburg, 2006; Wake, 2014).

Emerging Identity: Mathematics as Professional Toolset

This period of reflection also prompted mathematics departments and engineering programs to begin renegotiating their institutional relationship. Rather than treating service courses as simplified or diluted versions of mathematics-major curricula, educators increasingly recognized engineering mathematics as a distinct domain with its own pedagogical requirements, content priorities, and learning objectives. This shift paralleled contemporaneous developments in other applied fields—physics, chemistry, and biology—that were similarly rethinking the design of introductory science instruction for students whose professional goals lay outside the discipline itself. The growing consensus was that effective service teaching required not only curricular adaptation but genuine collaboration between disciplinary communities (Croft et al., 2009; Quinnell & Thompson, 2010).

Several institutions responded by experimenting with separate mathematics tracks for engineering students, taught either by faculty with engineering backgrounds or through joint appointments spanning mathematics and engineering departments. While these early experiments achieved mixed success and often faced institutional resistance, they established precedents for the more radical reforms that would emerge in the 1990s.

THE CALCULUS REFORM MOVEMENT AND COMPUTATIONAL INTEGRATION (1980s-1990s)

The National Calculus Reform Initiative

The late 1980s witnessed what became perhaps the most visible and widely debated reform movement in the history of undergraduate mathematics education: the calculus reform movement. Spurred by evidence of declining student performance, persistently high failure rates in introductory courses, and growing concern that traditional calculus instruction prioritized symbolic manipulation at the expense of conceptual understanding and real-world application, the Mathematical Association of America (MAA) launched a sustained series of initiatives to fundamentally reimagine introductory calculus. The foundational report, "Toward a Lean and Lively Calculus" (Douglas, 1986), advocated for reduced emphasis on rote algebraic technique, substantially increased attention to conceptual understanding and authentic applications, and the purposeful integration of emerging computational technologies. The reform movement quickly galvanized both enthusiastic support and vigorous opposition, reflecting deep disciplinary disagreements about the nature and purpose of undergraduate mathematics (Steen, 1988; Tucker & Leitzel, 1994).

For engineering education specifically, the calculus reform movement held both particular promise and particular peril. On one hand, an applications-oriented, technology-enabled calculus sequence aligned naturally with the practical mathematical needs of engineering students, potentially bridging the persistent gap between abstract instruction and professional application. On the other hand, engineering faculty harbored significant concern that reducing students' algebraic fluency might leave them inadequately prepared for the demanding technical coursework that followed. The debates ignited by calculus reform—concerning the appropriate balance between conceptual understanding and technical skill, the role of computational technology in replacing or supplementing traditional methods, and the institutional question of which academic units should control service mathematics curricula—proved durable. These tensions continue to animate curriculum discussions in engineering mathematics to the present day (Grizzle, 2025; Pepin et al., 2021).

Differential Equations and Engineering Applications

Running in parallel with the calculus reform debate, a distinct but related movement sought to reimagine the teaching of differential equations for engineering students. The proceedings of the Swarthmore conference on differential equations in the engineering curriculum argued forcefully that traditional ordinary differential equations (ODE) courses—focused heavily on the mastery of analytical solution techniques for a narrow catalogue of equation types—were failing to prepare students adequately for the realities of modern engineering practice. With digital computing enabling robust numerical solutions to virtually any ODE or partial differential equation (PDE) system, reformers contended that the curriculum needed to shift decisively toward mathematical modeling, qualitative and geometric analysis, computational methods, and the contextual interpretation of solutions in engineering settings (Blanchard et al., 2012; Harris et al., 2015; Strang, 1991; West et al., 2012).

This critique led to substantial curricular experimentation. Some institutions developed integrated "calculus + differential equations" sequences that introduced ODEs earlier and emphasized modeling throughout. Others created separate "differential equations for engineers" courses that prioritized applications, numerical methods, and computational tools (MATLAB, Mathematica) over analytical techniques.

Early Computational Mathematics Integration

The 1990s also witnessed pioneering efforts to systematically integrate computational methods throughout engineering mathematics sequences, rather than relegating numerical techniques to isolated upper-division elective courses. Kaw et al. (2012) document the development of comprehensive open educational resources for undergraduate numerical methods, encompassing root-finding algorithms, linear systems, interpolation, ODEs, PDEs, optimization, and Fourier analysis. Crucially, these resources incorporated digital lectures, interactive demonstrations, self-assessment tools, and computational assignments—representing one of the earliest sustained examples of blended digital pedagogy in engineering mathematics education. The initiative demonstrated that computational and analytical instruction could be productively unified rather than treated as separate pedagogical tracks, a principle that would become increasingly central to curricular reform in subsequent decades.

Taken together, this period established several key principles that would prove enduringly influential in subsequent reform efforts: mathematics instruction should foreground engineering applications from the outset rather than deferring them to advanced courses; computational tools should be woven throughout the curriculum rather than confined to isolated "computer lab" sessions; and effective pedagogy should leverage technology to support conceptual visualization, mathematical exploration, and authentic problem-solving rather than treating computers as sophisticated calculators. These principles, though not universally adopted at the time, laid important groundwork for the more systematic transformations that followed in the 2000s and beyond (Crouch & Mazur, 2001; Prince, 2004). Advances in software environments such as MATLAB and Mathematica further supported these pedagogical shifts by giving students accessible platforms for symbolic computation, numerical simulation, and graphical analysis (Kiianovska et al., 2018), visualization, exploration, and problem-solving rather than merely using computers as fancy calculators.

ACCREDITATION, FLEXIBILITY, AND PROGRAM REDESIGN (1990s-2000s)

ABET Engineering Criteria 2000

A critical inflection point came with ABET's adoption of "Engineering Criteria 2000" (EC2000) in the mid-1990s, which fundamentally restructured engineering program accreditation. As detailed in Akera's "ABET & Engineering Accreditation: History, Theory, Practice" (2019), EC2000 shifted from prescriptive input-based criteria (specifying required courses, credit hours, and topics) to outcome-based criteria focused on what graduates should be able to do. While EC2000 retained requirements for mathematics and basic sciences, it granted programs substantial flexibility in how those requirements were structured and delivered.

This policy shift proved enormously catalytic for mathematics curriculum innovation at the program level. With outcomes rather than inputs now serving as the primary standard for accreditation (Lattuca et al., 2006), programs were free to experiment with non-traditional sequencing, integrated engineering-mathematics courses, just-in-time delivery of mathematical concepts, and a variety of alternative instructional formats—all without jeopardizing their accreditation standing. Felder and Brent (2003) documented in detail how engineering programs across the country leveraged this new flexibility to address persistent and well-documented problems: high attrition and failure rates in early mathematics courses, persistent student difficulty in connecting abstract mathematical content to engineering applications, and the frustration of delaying students' exposure to core engineering concepts while they completed multi-semester mathematics prerequisites. The EC2000 framework thus created institutional space for some of the most consequential curricular experiments of the subsequent decade (Prados, 1998; Sheppard et al., 2008).

The "Engineering-First" Mathematics Model

One prominent outcome of this flexibility was the "engineering-first" mathematics model, exemplified by programs at Worcester Polytechnic Institute and other institutions. The model, described in "Modern Mathematics Requirements in a Developing Engineering Program," reversed traditional sequencing: instead of requiring students to complete extensive mathematics prerequisites before beginning engineering coursework, students enrolled immediately in introductory engineering courses supported by a concurrent "essential mathematics for engineering" module covering only the mathematical tools needed for those specific applications.

Under this model, mathematics topics—including vector calculus, differential equations, linear algebra, statistics, and numerical methods—were delivered just-in-time as the requirements of engineering courses demanded them, and consistently in formats that made explicit their connection to the engineering contexts in which students were simultaneously working. Proponents of the engineering-first approach argued that it improved student motivation by providing immediate and tangible relevance; reduced early attrition by sustaining engagement through meaningful engineering content; and enhanced long-term retention of mathematical concepts that were learned within application contexts rather than in abstraction (Felder & Brent, 2003). Preliminary assessments of early adopters suggested gains in student engagement and persistence, though rigorous comparative outcome data remained limited.

However, implementation proved challenging. Mathematics departments sometimes resisted ceding control over curriculum sequencing; the model required careful coordination between engineering and mathematics faculty; and students who transferred between programs or institutions faced difficulties with non-standard course progressions. Nevertheless, the engineering-first model demonstrated that radical restructuring was feasible and could yield positive results, inspiring further experimentation elsewhere.

Broadening Mathematical Content

This period of accreditation-enabled flexibility also witnessed the systematic and significant expansion of required mathematics content beyond the traditional calculus-and-differential-equations sequence that had dominated engineering programs for decades. Linear algebra, which had long featured prominently in electrical and mechanical engineering curricula but had been comparatively underemphasized in other disciplines, became nearly universal across engineering programs. Statistics and probability, traditionally accorded minimal curricular space, gained increasing prominence as engineering practice became more data-driven and as the probabilistic dimensions of design, reliability, and risk assessment demanded more rigorous treatment. Discrete mathematics emerged as a required element in computer engineering and software-intensive programs. Numerical methods and computational mathematics, previously advanced electives, migrated into required curricula.

These curricular expansions reflected both evolving pedagogical understanding and the genuine transformation of engineering practice itself. Contemporary engineering increasingly demands facility with matrix computations (central to finite element analysis, signal processing, and machine learning), statistical reasoning (essential for quality engineering, experimental design, and data analysis), optimization algorithms (pervasive in design and operations), and discrete modeling (foundational to software and systems engineering)—all competencies poorly developed by curricula that remained centered on continuous calculus and analytical differential equations. The broadening of required mathematics thus represented not merely a pedagogical preference but a reasoned response to the changing technical demands of the profession (Liu et al., 2022).

DIVERSIFICATION AND DIGITAL PEDAGOGY (2000s-2010s)

Systematic Review of Emerging Practices

By the early 2000s, engineering mathematics education had diversified and evolved to an extent that made systematic review and synthesis both necessary and timely (Bressoud et al., 2013; Rasmussen et al., 2014). Pepin et al.'s (2021) comprehensive survey of international research—spanning peer-reviewed journals, conference proceedings, and didactic research networks—provided the field with one of its most rigorous and wide-ranging assessments of contemporary practice (see also Alpers et al., 2013; SEFI Mathematics Working Group, 2013). Their analysis identified several salient and interconnected trends that were reshaping engineering mathematics instruction globally:

- **Content diversification:** Beyond traditional calculus and differential equations, programs increasingly incorporated linear algebra, statistics, numerical analysis, optimization, and computational modeling, reflecting engineering's expanding mathematical toolkit.
- **Pedagogical innovation:** Active learning, project-based tasks, flipped classrooms, peer instruction, and technology-enhanced instruction were replacing traditional lecture-based delivery, particularly for engineering students (Crouch & Mazur, 2001; Freeman et al., 2014; Prince, 2004).
- **Integration with engineering contexts:** Rather than teaching mathematics abstractly and then expecting transfer to engineering applications, curricula are increasingly embedding mathematical concepts within engineering problems from the outset.
- **Digital resources and tools:** Online homework systems, computational software (MATLAB, Python, Mathematica), visualization tools, and open educational resources transformed both instruction and assessment (Kaw et al., 2012; Loch et al., 2014).

Notwithstanding these encouraging developments, Pepin et al. (2021) also identified significant and persistent limitations. The adoption of innovative practices remained highly uneven, often confined to individual instructors or isolated programs rather than diffusing systematically across institutions. Rigorous empirical evaluation of innovative curricula—employing controlled designs, meaningful comparison groups, and longitudinal outcome tracking—remained rare. Moreover, engineering mathematics education as a research field continued to lag behind the broader mathematics education research community in both theoretical sophistication and methodological rigor, limiting the generalizability of available findings. These observations highlighted the pressing need for a more mature and systematic research infrastructure to support evidence-based practice in engineering mathematics education.

Competency frameworks: Rethinking what engineers need to know

A central contribution of Pepin et al.'s (2021) review is its synthesis of efforts to move beyond lists of mathematical topics toward genuine competency-based frameworks for engineering mathematics curricula. The landmark work of the European Society for Engineering Education (SEFI, 2013), drawing on Niss's (2003) foundational conceptualization of mathematical competence as 'the ability to understand, judge, do, and use mathematics in a variety of intra- and extra-mathematical contexts,' proposed organizing engineering mathematics curricula around eight competencies: thinking mathematically, reasoning mathematically, posing and solving problems, modelling mathematically, representing mathematical entities, handling mathematical symbols and formalism, communicating in, with, and about mathematics, and making use of aids and tools. This competency-based approach was a deliberate departure from the content-inventory logic that had dominated engineering mathematics curriculum design for decades — a logic that asked 'what topics should students cover?' rather than 'what should students be able to do with mathematics?'

The implications of this shift are substantial for curriculum designers. A competency orientation demands that assessments, pedagogical activities, and course sequencing be evaluated not simply by whether they expose students to required content but by whether they develop transferable mathematical abilities applicable across engineering contexts. Deeken et al. (2020), in a systematic Delphi study of German engineering instructors, found that university teachers expected students not only to master specific content but to demonstrate 'mathematical flexibility' — the ability to apply familiar mathematical processes in unfamiliar situations. This expectation is poorly served by curricula organized exclusively around procedural fluency in standard problem types. Faulkner et al. (2019) similarly found that engineering faculty placed high value on 'mathematical maturity' — encompassing strong modelling competence, symbolic fluency, and purposeful use of computational tools — yet reported that students' actual abilities in these areas fell significantly short of expectations, particularly their capacity for mathematical modelling.

Mathematical modelling as a cornerstone of engineering mathematics

Among the themes emerging from Pepin et al.'s (2021) review, mathematical modelling occupies a uniquely prominent position as both an instructional challenge and a promising avenue for innovation. Modelling is close to the core of engineering practice in a way that abstract symbol manipulation is not: engineers routinely translate physical systems into mathematical representations, analyze those representations, and interpret results back in physical terms. Yet traditional engineering mathematics curricula have largely failed to develop these capacities explicitly, teaching instead the analytical solutions to pre-formulated equations without requiring students to construct the models themselves.

Several studies reviewed by Pepin et al. document attempts to embed genuine modelling tasks in engineering mathematics courses. Wolf (2017) developed engineering-contextualized modelling tasks for weekly homework in a first-year mathematics course that had previously been taught without any explicit applications reference. Evaluations showed positive effects on student motivation, particularly for students who identified as application-oriented — though these effects were attenuated when students realized modelling tasks were not represented in examinations, highlighting the critical role of assessment alignment. Härterich et al. (2012) demonstrated that hands-on modelling projects — using differential equations to model an inverted pendulum, or trigonometric functions to model crane oscillations — produced substantial gains in students' motivation and their understanding of mathematical relevance, including for topics as abstract as eigenvalues and Taylor expansions. Studies using the Anthropological Theory of Didactics (ATD) have further demonstrated that different institutional contexts — mathematics courses versus engineering science courses — generate fundamentally different 'praxeologies' around the same mathematical objects. For example, González-Martín and Hernandes-Gomes (2018) showed that integrals in a mathematics course involved praxeologies with strong theoretical components, while the same concept in a strength-of-materials course required only basic calculation. Students navigating these institutional transitions without explicit support are left to bridge radically different epistemological frameworks on their own.

Student identity, self-efficacy, and affect in engineering mathematics

Pepin et al.'s (2021) review devotes considerable attention to the affective and identity dimensions of engineering students' mathematical learning — dimensions that the manuscript has addressed in section 8.1 but which deserve additional grounding in the international comparative literature. A key insight from this body of work is that students' mathematical difficulties are not purely cognitive but are deeply entangled with questions of identity and self-perception. Harris et al. (2015), through interviews with engineering students experiencing mathematical difficulties at the secondary-tertiary transition, found that these students primarily valued mathematics for its 'use-value' and 'exchange-value' — they wanted to see mathematics as a functional tool for engineering and as a credential for degree completion — but often failed to develop a productive identity as mathematical learners in the engineering context. This finding resonates with Goold's (2014) observations about Irish engineering students' predominantly extrinsic and examination-oriented mathematics motivation, and extends it to a multi-institutional comparative context.

Kaspersen et al. (2017) quantified these identity effects, finding that engineering students reporting high mathematical identities achieved grades approximately one full grade higher on average than students with low mathematical identities, and that this association was particularly strong at high identity levels. This suggests that mathematical identity is not merely a correlate of competence but a meaningful amplifier of it — students who see themselves as capable mathematical learners differentially invest in and benefit from mathematical instruction. Self-efficacy research by Kürten (2017) further showed that pre-university bridging courses can produce sustained gains in both mathematical and social self-efficacy, with effects persisting at least three months beyond course completion — a finding with direct implications for the design of transition support programs. Taken together, these studies suggest that interventions targeting mathematical identity and self-efficacy may be at least as important as curricular content changes for improving engineering mathematics outcomes.

Assessment innovation: From high-stakes examinations to formative feedback

A recurring theme in Pepin et al.'s (2021) review is the misalignment between innovative pedagogical practices and traditional assessment systems. Several studies document instances where student motivation improvements generated by modelling tasks, active learning, or context-rich instruction were subsequently undermined when students discovered that final examinations tested only procedural skills. This constructive misalignment — in which innovative teaching is not matched by innovative assessment — limits the durability and depth of learning gains. As Pepin et al. conclude, 'if innovative design does not go hand-in-hand with new assessment systems that reflect the new goals (constructive alignment), an innovation may not have a lasting effect.'

Formative assessment practices emerge from this literature as one of the more promising approaches to realigning incentives with learning goals. Gaspar Martins (2017) found that weekly online homework quizzes used as formative assessment produced high student engagement and were rated as fair and useful by nearly all participants. Griese and Kallweit (2017) demonstrated that changing assessment formats from multiple-choice to open-ended questions shifted students toward deeper learning behaviors, while Griese's (2017) longitudinal design-research project showed that a coordinated system of learning strategy interventions — embedding metacognitive practices across the course website, workbooks, helpdesk, and mentoring sessions — produced meaningful improvements in both learning approaches and examination outcomes. These studies collectively suggest that assessment reform is not a peripheral concern but a lever of central importance for realizing the full potential of curricular innovation in engineering mathematics.

Techno-mathematical literacies and the digital resource landscape

The review by Pepin et al. (2021) identifies 'techno-mathematical literacies' (TmL) — originally conceptualized by Kent and Noss (2003) and refined by Van der Wal et al. (2017, 2019) — as one of the most theoretically significant recent contributions to understanding what mathematical competencies contemporary engineers actually need. TmL describes the combined mathematical and information technology competencies required for technically mediated workplace tasks: not just knowing mathematics and knowing computing tools separately, but being able to reason critically through and with technological mediations of mathematical content. In a project-based course designed to develop TmL, Van der Wal et al. (2019) found that requiring students to present and collectively discuss their computational work — including explaining why software produced particular results — cultivated a reflective relationship with digital tools that extended beyond computation to genuine mathematical reasoning.

This emphasis on TmL is directly relevant to contemporary discussions of data science and AI integration in engineering mathematics curricula. The competencies that TmL identifies — purposeful tool use, critical interpretation of computational outputs, validation of algorithmic results — are precisely those that the most recent literature identifies as central to AI-ready engineering practice (Beyazhancer & Demir, 2025). Pepin et al. (2021) further observe that students' management of digital and non-digital learning resources is itself an underappreciated dimension of mathematical learning: Kock and Pepin (2018) found that first-year engineering students frequently imported secondary school resource strategies into university mathematics courses with inadequate results, and that explicit support for resource orchestration — particularly in large courses — could substantially improve learning outcomes. These findings suggest that future curriculum frameworks should address not only what content students learn but how students navigate the increasingly complex ecology of digital mathematical resources in which that learning takes place.

Linear Algebra for Engineers

Among the mathematical topics that gained expanded prominence in engineering curricula during this period, linear algebra emerged as simultaneously the most critical and the most pedagogically challenging. While linear algebra constitutes the mathematical foundation for virtually all computationally intensive engineering applications—including finite element analysis, control systems design, digital signal processing, optimization, and machine learning (Liu et al., 2022; Strang, 1991)—traditional linear algebra courses have historically emphasized abstract vector spaces, formal theoretical proofs, and the algebraic structure of matrix theory in ways that engineering students consistently struggle to connect with their professional applications. Li and Chen (2024), in a systematic review of more than fifty empirical and pedagogical studies, proposed a set of instructional design principles specifically tailored to the needs and learning contexts of engineering students:

- **Applications over abstraction:** prioritizing practical concepts (systems of equations, least-squares, eigenvalues in engineering contexts) over abstract theory
- **Computational methods:** integrating numerical linear algebra and matrix computations
- **Visualization and geometric interpretation:** using software to visualize transformations, span, and subspaces
- **Active learning:** flipped classrooms, group problem-solving, and projects
- **Engineering contexts:** examples from circuits, structures, control systems, and data analysis throughout

This work exemplifies a broader trend: rather than expecting engineering students to adapt to mathematics-major curricula, mathematics education was adapting to engineering students' needs, learning styles, and professional contexts.

ICT and Digital Transformation

The 2000s-2010s witnessed the accelerating integration of information and communication technologies (ICT) into mathematics instruction. Kiianovska, Rashevska, and Semerikov's "Development of Theory and Methods of Use of ICT in Teaching Mathematics of Engineering Specialties Students in the United States" (2018) traced six stages in ICT adoption for engineering mathematics education in U.S. universities:

1. **Early calculators** (1970s): Basic computational aids
2. **Personal computers and spreadsheets** (1980s): Data analysis and simple modeling
3. **Computer algebra systems** (1990s): Symbolic manipulation and visualization
4. **Internet and online resources** (2000s): Digital textbooks, video lectures, online homework
5. **Integrated learning environments** (2010s): Learning management systems, adaptive software, collaborative platforms
6. **Mobile and cloud computing** (2015+): Anywhere/anytime access, computational notebooks, real-time collaboration

Each stage enabled new pedagogical possibilities while also creating digital divides between well-resourced and under-resourced institutions and raising questions about appropriate roles for technology in mathematics learning.

CONTEMPORARY DEVELOPMENTS: DATA, AI, AND RADICAL REDESIGN (2020s)

Rethinking Foundations for the Modern Engineer

The most recent literature reflects an increasingly ambitious and at times radical rethinking of how engineering mathematics should be structured from its foundations. As the technological environment of engineering practice has shifted dramatically toward computation, simulation, and data analysis, the inherited structure of the mathematics curriculum—organized around sequences developed for a very different era—has come under intensifying scrutiny. Representative of this emerging perspective, Grizzle (2025) proposes a comprehensive redesign of the undergraduate calculus sequence built around four interconnected principles:

- Integrating integral calculus, differential calculus, multivariable calculus, and ODEs into a unified two-semester sequence
- Emphasizing computational thinking and programming (using Julia) from day one
- Building all content around authentic engineering applications
- Developing both symbolic and numerical solution strategies in parallel
- Treating modeling, simulation, and validation as central rather than peripheral

Grizzle argues that traditional separation of calculus topics is a historical accident rather than a pedagogical necessity, and that modern computational tools enable teaching approaches infeasible a generation ago. While Grizzle's proposal remains to be tested at scale, it represents contemporary thinking about how engineering mathematics might be reimagined, given current technological capabilities and engineering practice.

Computational Mathematics for Technology-Based Practice

Kamalov and Leung (2022) offer a pragmatic and institutionally sensitive contribution to this conversation, arguing for the strategic augmentation of traditional mathematics curricula with computational mathematics content to better align instruction with the demands of technology-driven engineering workplaces. Rather than advocating wholesale curriculum replacement, they propose embedding numerical linear algebra, computational simulation, and data analysis alongside classical analytical mathematics in a manner designed to strengthen coherence rather than create fragmentation. Their "minimal-resources" approach is explicitly oriented toward adoption feasibility: rather than requiring comprehensive curriculum overhauls that many departments lack the resources or institutional will to undertake, they recommend targeted additions and modifications that can incrementally build students' computational competency within existing course structures.

This pragmatic approach appropriately acknowledges the institutional realities that constrain curriculum reform—limited faculty time, budget pressures, accreditation requirements, and significant coordination challenges between mathematics and engineering departments—while still pursuing meaningful and measurable curriculum evolution. Its risk, however, lies in the potential for fragmentation: appending computational modules to existing courses without achieving deeper conceptual integration may produce students who can execute computational procedures without developing the cohesive computational-mathematical thinking that modern engineering increasingly requires. The tension between incremental feasibility and transformative effectiveness represents one of the central unresolved challenges for reformers in this space (Austin, 2011; Kezar, 2018).

Data Science, AI, and Techno-Mathematical Literacy

Perhaps the most pressing and consequential contemporary challenge facing engineering mathematics educators is the need to integrate data science, artificial intelligence, and machine learning into a curriculum that was not designed to accommodate them. As AI-driven tools become embedded in engineering workflows—from design optimization and materials discovery to predictive maintenance and autonomous systems (Brynjolfsson & McAfee, 2014)—the mathematical literacy required for engineering practice has expanded in both breadth and character. Beyazhancer and Demir (2025) report that AI-supported learning experiences in undergraduate engineering courses produced significant improvements in students' "techno-mathematical literacy"—broadly defined as the ability to leverage computational tools purposefully, interpret algorithmic outputs critically, and apply mathematical reasoning in technology-mediated contexts—as well as in their self-efficacy when working with AI systems. These findings point toward an emerging pedagogical paradigm in which mathematical competency and computational fluency are developed simultaneously and in mutual reinforcement (Weintrop et al., 2016; Wing, 2006).

This body of work reflects a growing and well-founded recognition that contemporary engineers operate in environments where mathematical computation is largely automated, data generation is pervasive and continuous, and AI systems have assumed responsibility for many tasks that once demanded direct human mathematical intervention. Under these conditions, the mathematical competencies engineers require have shifted substantially toward: statistical reasoning and principled uncertainty quantification; algorithmic thinking and the design of computational workflows; data preprocessing, feature engineering, and the interpretation of high-dimensional datasets; rigorous validation and verification of computational results; and the critical evaluation of AI model outputs—including an understanding of their underlying mathematical assumptions and failure modes. Landgärds-Tarvoll (2024) further highlights that these emerging competency demands compound the longstanding challenge of supporting students through the secondary-to-tertiary transition in mathematics, where foundational gaps can undermine readiness for advanced computational training.

Traditional mathematics curricula—designed for an era of hand calculation and closed-form analytical solution—are structurally and substantively ill-suited to prepare students for these demands. Several programs have begun developing what

Table 1. Predictive relationships between foundational math courses and second-year engineering performance (Whitcomb et al., 2020)

Target Course (Semester)	Strongest Predictor	2nd Predictor	R^2 adj (approx.)	Key Implication
ECE Circuits (S3)	Diff. Equations	Engineering 1	.42–.44	Linear Algebra taken before circuits improves performance (ANCOVA confirmed)
Materials Structure (S3)	Calculus 3	Linear Algebra	.38–.40	Math sequence quality directly predicts materials science success
Mechanics 1 (S3)	Calculus 3	Linear Algebra	.39–.38	Physics 2 also predictive; math + physics foundations both matter
Mechanics 2 (S4)	STEM GPA (cumul.)	Diff. Equations	.50–.53	Linear Algebra stronger predictor than Mechanics 1 itself by S4
MEMS Circuits (S4)	STEM GPA (cumul.)	Linear Algebra	.43–.46	Predictive relationship is linear, not threshold — higher math grades always matter

might be termed “data-aware mathematics” or “AI-informed mathematics” courses that seek to build bridges between classical mathematical content and contemporary data science practice, though these efforts remain largely experimental, localized, and not yet subject to rigorous comparative evaluation. The field lacks both consensus on what an “AI-ready” engineering mathematics curriculum should contain and the empirical evidence needed to evaluate competing proposals.

Curriculum Structure and Bottleneck Analysis

Recent research has adopted systems-level perspectives on mathematics curricula. The 2025 working paper “The Topology of Hardship: Empirical Curriculum Graphs and Structural Bottlenecks in Engineering Degrees” (Paz, 2025) analyzes prerequisite networks across 29 engineering programs, treating curricula as directed graphs where courses are nodes and prerequisites are edges. The analysis identifies mathematics courses—particularly service mathematics courses—as central structural bottlenecks that strongly influence student progression, time-to-graduation, and dropout risk.

This work suggests that beyond content and pedagogy, the organization and sequencing of mathematics requirements profoundly shape student experiences and outcomes. Programs with highly sequential mathematics prerequisites (where each course requires completing previous courses) create “hardship chains” that delay students and increase attrition risk. More flexible structures with fewer prerequisites, alternative pathways, and concurrent enrollment options may improve retention while maintaining mathematical competency.

Empirical Evidence for the Predictive Power of Foundational Mathematics Courses

Institutional data analytics: From correlation to actionable evidence

One of the most methodologically rigorous contributions to the question of foundational mathematics’ role in engineering success comes from Whitcomb et al. (2020), whose analysis of ten years of institutional data from 5,348 engineering students at a US research university provides compelling quantitative evidence that performance in mathematics foundational courses linearly predicts performance in second-year engineering courses — above and beyond general student ability. Using a stepwise multiple regression framework with z-scored grades and controls for high school GPA, SAT Math scores, and cumulative STEM GPA, the study examined predictive relationships across courses in Mechanical Engineering and Materials Science (MEMS) and Electrical and Computer Engineering (ECE) curricula.

Three findings are particularly relevant for engineering mathematics curriculum design. First, the relationship between foundational course grades and later engineering performance is linear rather than threshold in character: students who earn an A in Calculus or Linear Algebra consistently outperform students who earn a B, who consistently outperform students who earn a C, at every level of subsequent engineering coursework. This finding empirically refutes the informal ‘Cs get degrees’ advice that circulates among students, and it suggests that academic advisors and instructors should actively encourage students to pursue high rather than merely passing grades in foundational mathematics. Second, advanced mathematics courses — particularly Calculus 3, Linear Algebra, and Differential Equations — are the strongest course-specific predictors of second-year engineering performance, often outperforming same-discipline foundational courses as predictors. Third, chemistry courses, despite their inclusion in most engineering curricula, ceased to be significant predictors once cumulative STEM GPA was controlled for, suggesting they may be proxies for general academic ability in physics-intensive engineering programs rather than providing specific transferable knowledge.

The contrast between ECE Circuits and MEMS Circuits courses in Whitcomb et al.’s analysis provides a particularly instructive natural experiment. These courses cover near-identical content but differ in when Linear Algebra is required relative to them: MEMS students take Linear Algebra before circuits; ECE students typically take it concurrently or after. Controlling for prior math ability via SAT scores and high school GPA, students who had completed Linear Algebra before or concurrently with the circuits course significantly outperformed those who had not. This finding directly supports the argument that curricular sequencing of mathematics prerequisites is not merely administrative but has measurable consequences for student learning, and it provides empirical grounding for arguments in favor of careful prerequisite design. Together, these findings validate the mathematical foundations embedded in engineering programs and provide advisors and curriculum designers with evidence-based tools for explaining to students why taking foundational mathematics seriously — and aiming for more than a passing grade — matters for their long-term engineering success (see **Table 1** for a summary of key predictive relationships).

Mathematics as a Barrier Course in Engineering Attrition

Qualitative evidence from student departure narratives

Whitcomb et al.'s (2020) quantitative findings on the predictive power of mathematics are given human texture by Meyer and Fang's (2019) qualitative case study of five engineering students who left their programs at a large public research university. Using semi-structured interviews and participant-generated journey maps, Meyer and Fang uncovered two themes common to all five departures: a gradual erosion of connection and interest in engineering, and a barrier course that acted as a final precipitating factor in the decision to leave. Three of the five students named a calculus course as the barrier course — Calculus I in two cases and Calculus III in a third — a pattern the authors describe as consistent with existing quantitative literature on engineering attrition (Tyson, 2011).

The departure narratives illuminate the mechanisms through which mathematics courses become barriers. One participant described spending three-quarters of his total homework time on Calculus I while still failing, leading him to conclude that the social isolation required to succeed in engineering was incompatible with his broader goals. Another failed Calculus III and concluded that the stress of mathematics had become unsustainable. A third was discouraged by receiving his first-ever B grade in a manufacturing course and began questioning whether engineering was the right field — a decision that calculus subsequently confirmed. These accounts highlight how mathematics courses, when students lack both adequate preparation and a clear sense of mathematics' relevance to their engineering identity, can precipitate departure decisions that might have been preventable with different curricular or advising interventions.

Participants' own retrospective advice to the engineering programs they left echoes themes from the broader curriculum literature: help students understand the intensity of the commitment required before they begin; create more hands-on experiences that connect classroom mathematics to engineering practice; and be mindful of how the transition from consistent academic success to struggling — often first encountered in calculus — can be psychologically destabilizing. The Meyer and Fang findings thus complement Goold's (2014) motivational evidence and Kenyon and Benson's (2025) assessment perceptions research, forming a coherent body of evidence suggesting that mathematics's role as an engineering barrier is substantially a function of pedagogy, framing, and student support — not merely content difficulty.

MATHEMATICS AS A BARRIER COURSE IN ENGINEERING ATTRITION

Student Readiness and Misconceptions

Despite decades of sustained curricular reform, fundamental challenges rooted in student mathematical preparation continue to impede progress. A 2025 literature review cataloguing mathematical misconceptions across engineering disciplines documents a consistent pattern of persistent student difficulties: weak algebraic foundations, limited trigonometric fluency, systematic misconceptions regarding the nature of functions and variables, and inadequate proportional reasoning (Sirokman et al., 2025). A substantial proportion of engineering students arrive underprepared for calculus-based instruction despite having completed nominally prerequisite courses, a pattern that implicates both significant gaps in K-12 mathematical preparation (ACT, 2016; Crisp et al., 2009) and structural misalignments between secondary and post-secondary expectations. Landgärds-Tarvoll (2024) characterizes this secondary-to-tertiary transition as a distinct and underappreciated challenge, noting that the shift from procedural school mathematics to the conceptual and proof-oriented demands of university mathematics represents a qualitative discontinuity for which many students receive inadequate support (Gueudet, 2008; Tall, 2008).

Moreover, misconceptions extend beyond procedural errors to fundamental conceptual misunderstandings about derivatives, integrals, probability, and linear transformations. These persist even after students pass relevant courses, undermining their ability to apply mathematics in engineering contexts. Remediation efforts—bridge programs, supplemental instruction, co-requisite support—show promise but remain under-resourced and poorly integrated into degree programs (Croft et al., 2009; Matthews et al., 2013).

Student value formation and the role of investigative learning

A persistent finding in the literature is that engineering students who struggle with mathematics do so not merely because of cognitive deficits but because they fail to perceive meaningful value in what they are learning. Goold's (2014) qualitative study of seventeen part-time energy engineering students at an Irish Institute of Technology offers a particularly illuminating case. Using Wigfield and Eccles' (2002) expectancy-value framework as the theoretical lens, Goold found that the majority of students entered her study with exclusively extrinsic motivations for studying mathematics: passing examinations. Their learning strategy was universally rote — practicing past examination questions in isolation, without any mathematics learning goals, and with no social engagement around mathematical ideas. These students did not discuss mathematics outside lectures except to question its relevance, and they showed marked reluctance to depart from procedural rules or engage in open-ended mathematical inquiry.

The intervention Goold introduced—requiring students to independently investigate how professional engineers use mathematics in their own field—produced a striking shift. After completing the investigation, every student in the study reported an increased awareness of the usefulness of mathematics in engineering practice, and several described the experience as transformative. This shift from purely extrinsic to utility-oriented motivation was achieved not through changes to the mathematical content itself but through changes in the context within which students encountered that content. Goold's findings draw on her broader doctoral research (Goold, 2012), in which she documented that practicing engineers employ a wide range of mathematical skills in professional settings and that the ability to communicate mathematical ideas—in writing and to non-

Table 2. Calculus exam purpose perceptions and curriculum/assessment design responses (Kenyon & Benson, 2025)

Exam Purpose Perception	Student Instrumentality Orientation	Associated Student Behavior / Risk	Curriculum / Assessment Design Response
Performance-Driven (Individual)	Endogenous PI of Calculus and exams	Motivated self-assessment; uses exams to identify gaps	Affirm this perception; design exams with self-reflection components
Future-Oriented	Endogenous PI of Calculus; sees content as relevant to career	Motivated to learn content; connects coursework to professional goals	Reinforce by embedding engineering contexts; link exam tasks to real problems
External	Exogenous PI; grade-focused, performance for others	Extrinsic motivation; 'earn a grade' mentality; disengages from understanding	Reduce grade-weighting of single exams; add formative, low-stakes assessments
Adverse	Exogenous PI of both Calculus and exams; sees neither as relevant	Highest math test anxiety; contingent-goal fragility; dropout risk	Provide explicit engineering relevance; reduce single-exam stakes; offer error-correction opportunities

specialist audiences—is a professional competency that engineering programs rarely develop explicitly. These two contributions are complementary: the PhD thesis establishes what mathematics means in engineering practice; the 2014 conference paper tests whether connecting students to that practice can shift their motivation.

These findings align with a broader body of literature arguing that engineering students' negative relationships with mathematics are substantially a function of how mathematics is taught, not simply what mathematical content is covered (Harris et al., 2015; Nardi & Steward, 2003). Relevance and perceived utility can be cultivated deliberately through pedagogical design, and this cultivation can have downstream effects on engagement, effort, and persistence. Goold's study also highlights a dimension of mathematical competency that engineering education often neglects: the ability to communicate mathematics. Students in her study found it difficult to put mathematical equations into written documents and to describe mathematical ideas without the security of procedural rules — a weakness that engineering programs rarely address explicitly, yet which practicing engineers identify as a significant professional gap.

Assessment Perceptions and Future-Oriented Motivation

How engineering students perceive the purpose of calculus assessments

Complementing the literature on mathematics motivation, recent empirical work by Kenyon and Benson (2025) provides some of the most nuanced and methodologically sophisticated insights into how engineering students relate to calculus assessments. Conducted at a large R1 land-grant university in the southeastern United States, this mixed-methods study combined survey data from over 900 first-year engineering students with interpretive phenomenological analysis (IPA) of individual interviews. The study found that first-year engineering students perceive the purpose of Calculus I examinations in four distinct ways: with a Performance-Driven Purpose (understanding as a gauge of competency), a Future-Oriented Purpose (preparation for courses or careers), an External Purpose (earning a grade), or an Adverse Purpose (stress-inducing, purposeless, or harmful). Critically, these perceptions are not mutually exclusive — students often held multiple orientations simultaneously.

The study's most consequential finding concerns the interaction between assessment perceptions, Future Time Perspective (FTP), and math test anxiety. Drawing on Husman and Lens's (1999) framework of perceived instrumentality, Kenyon and Benson found that when students held an endogenous perceived instrumentality of Calculus content itself — that is, when they genuinely saw calculus concepts as relevant to their future in engineering — they remained motivated to learn even when they disliked the exams. However, when students held an exogenous perceived instrumentality of both calculus and its assessments (seeing neither as connected to their engineering futures), their math test anxiety intensified. This pattern was most severe among students whose near-term goals depended contingently on their Calculus I exam grade — whose scholarship retention, program continuation, or personal identity as a future engineer was tied directly to performance. For such students, calculus exams functioned as high-stakes gatekeepers in a fragile chain of dependencies rather than as developmental learning milestones.

These findings carry direct implications for assessment design in engineering mathematics. Kenyon and Benson argue that explicit communication of assessment purpose — particularly its relationship to professional competency formation — can meaningfully shift students toward more productive exam perceptions. Syllabi that state only examination weights without articulating pedagogical purpose inadvertently reinforce extrinsic and adversarial interpretations. Assessment designs that incorporate self-reflection, error-correction, and formative feedback alongside summative examinations may distribute the stakes more equitably while preserving the diagnostic value that performance-driven students find useful. Reducing the fraction of a course grade determined by a single high-stakes exam — while maintaining academic rigor — could substantially mitigate math test anxiety for the most vulnerable students without compromising curriculum standards (Kenyon & Benson, 2025; McArthur et al., 2022). **Table 2** summarizes the four exam-purpose perception types and associated assessment design responses.

Application and Transfer Difficulties

Even students who demonstrate technical mastery of mathematical procedures frequently encounter significant difficulties when attempting to deploy that knowledge in authentic engineering contexts—a phenomenon reflecting a deeper and more troubling dimension of the preparation problem. Ovodenko and Kouropatov (2025) provides a detailed empirical account of the cognitive obstacles that impede engineering students' mathematical modeling, documenting recurring and systematic difficulties in translating between mathematical representations and the physical contexts they are meant to describe. Students who can solve differential equations competently in symbolic form often fail to recognize when a physical system requires an ODE model

(Bingolbali et al., 2007); students who can manipulate matrices fluently are nonetheless unable to formulate an engineering problem as a linear system; students who can calculate integrals accurately do not reliably identify when integration is the appropriate tool for a given real-world quantity. These findings reveal a fundamental gap between procedural facility and conceptual applicability that persists across diverse mathematical domains and student populations.

These pervasive transfer failures suggest that the traditional structural separation between mathematics instruction and engineering application—even in courses that include engineering-inflected examples—fails to develop the cognitive flexibility, contextual judgment, and situational awareness that professional engineering practice demands. The literature increasingly suggests that more deeply integrated curricula—in which mathematical concepts emerge from genuine engineering problems and are subsequently applied back to them in iterative cycles—may more effectively support the development of transferable mathematical competency. Nevertheless, rigorous empirical evidence for this hypothesis remains limited, and the design principles for achieving productive integration at scale are not yet well established (Ovodenko & Kouropatov, 2025; Pepin et al., 2021).

Epistemological Tensions

A deeper and perhaps irreducible source of curricular tension lies at the epistemological level, in the distinct and sometimes incompatible ways of knowing that characterize mathematics and engineering as disciplines. Edström (2018), in a historically informed analysis, identifies fundamental tensions between mathematical and engineering epistemologies that persistently complicate curriculum design and institutional negotiation. Mathematics as a discipline prizes abstraction, generality, formal rigor, and proof as its primary epistemic virtues; engineering, by contrast, prizes particularity, adequacy for purpose, practical utility, and effective design. These different orientations toward knowledge create ongoing and structurally persistent conflicts in the context of service education:

- Should engineering mathematics emphasize theoretical understanding or practical competency?
- Is mathematical rigor essential for engineering thinking or an unnecessary hurdle?
- Should computational methods supplement or potentially replace analytical techniques?
- Who should control engineering mathematics curricula—mathematics departments or engineering programs?

These are not merely administrative or pedagogical questions but reflect deeper disciplinary identities and values (Burton, 1999; Ernest, 1998). The literature suggests no simple resolution; successful programs navigate these tensions through ongoing dialogue, mutual respect, and institutional willingness to experiment (Lattuca & Stark, 2009; Trowler, 2008).

Implementation Barriers and Institutional Inertia

Despite an extensive and growing body of literature documenting innovative practices and their apparent benefits, systematic reviews consistently note that actual adoption of these innovations across the broader engineering education community remains limited, geographically and institutionally uneven, and frequently unsustained over time. Pepin et al. (2021) observe that the majority of documented reforms remain isolated experiments by individual instructors, rarely scaling to the department or institutional level. Even demonstrably successful pilots frequently revert to traditional instructional formats when the driving faculty member departs or when institutional priorities and resource allocations shift. This persistent gap between demonstrated innovation and widespread adoption represents one of the most consequential and least-understood phenomena in engineering mathematics education research (Andrews & Lemons, 2015; Borrego & Henderson, 2014).

Several factors contribute to this inertia:

- **Faculty capacity and training**: Teaching integrated, computationally-oriented, application-rich mathematics requires expertise spanning mathematics, computation, and engineering—a rare combination. Professional development opportunities are limited.
- **Departmental structure**: Traditional separation between mathematics departments (responsible for service courses) and engineering departments (the consumers of those services) creates coordination challenges and diffuse accountability.
- **Resource constraints**: Developing new curricula, creating computational materials, coordinating across departments, and assessing outcomes require time and funding often unavailable.
- **Risk aversion**: Administrators and faculty worry that experimental curricula might compromise student preparation, accreditation compliance, or transfer articulation.
- **Assessment challenges**: Measuring whether innovative mathematics instruction improves engineering competency requires longitudinal tracking and multifaceted assessment—rarely feasible at scale.

These barriers suggest that sustained curricular transformation requires not just pedagogical innovation but institutional redesign, strategic resource allocation, and systematic assessment infrastructure.

SYNTHESIS: PATTERNS, TRENDS, AND TRAJECTORIES

Examining six decades of evolution in engineering mathematics education reveals several overarching patterns:

- **From Prerequisite to Integrated Tool:** Mathematics has transitioned from a gate-keeping hurdle to be cleared before “real” engineering coursework toward an ongoing support tool for modeling, design, computation, and analysis. This shift reflects both pedagogical insight (mathematics learned in application transfers better) and practical reality (engineers use mathematics throughout their careers, not just in prerequisites).

- **Content Diversification Beyond Calculus:** While calculus and differential equations remain foundational, contemporary curricula incorporate linear algebra, statistics, numerical methods, optimization, discrete mathematics, and emerging topics (data science, machine learning, uncertainty quantification). This diversification reflects engineering's expanding mathematical toolkit and recognition that modern engineering requires broader mathematical competency than traditional calculus-centered curricula provide.
- **Computational Transformation:** Digital computing has fundamentally transformed both engineering practice and mathematics education. Instruction has shifted from hand calculation toward computational modeling, numerical simulation, and data-driven analysis. This is not merely "adding computers" to existing curricula but reconceptualizing what mathematical competency means when computational power is ubiquitous.
- **Pedagogical Evolution Toward Active Learning:** Traditional lecture-based, proof-oriented mathematics instruction has gradually given way to active learning, project-based tasks, flipped classrooms, collaborative problem-solving, and technology-enhanced pedagogy—particularly for engineering students, whose learning styles and professional goals differ from mathematics majors.
- **Accreditation-Enabled flexibility:** Policy changes, particularly ABET EC2000's outcome-based criteria, provided institutional space for experimentation. This flexibility enabled innovations like just-in-time mathematics, engineering-first sequencing, and integrated curricula—though adoption remains uneven.
- **Persistent Structural Challenges:** Despite reforms, mathematics courses remain major bottlenecks in engineering degree programs, contributing to delayed graduation and attrition. Student readiness gaps, transfer difficulties, and epistemological tensions between mathematics and engineering persist as ongoing challenges.
- **Emerging Frontiers: Data, AI, and Professional Relevance:** The most recent literature emphasizes data science, artificial intelligence, techno-mathematical literacy, and explicit mapping of mathematical training to workplace demands—suggesting the evolution continues accelerating.

CRITICAL ANALYSIS: GAPS AND LIMITATIONS IN CURRENT LITERATURE

Despite a rich body of scholarship, significant gaps limit our understanding of engineering mathematics education evolution:

- **Lack of Comprehensive Longitudinal Data:** Few studies systematically track mathematics curricula across multiple institutions and decades. Most scholarship consists of single-institution case studies or cross-sectional surveys, limiting ability to generalize about trends, effectiveness, or sustainability of reforms.
- **Insufficient Empirical Linkage to Student Outcomes:** While literature documents curriculum changes and pedagogical innovations, rigorous evidence connecting specific reforms to measurable outcomes (retention, graduation rates, engineering competency, career success) remains scarce. Claims about effectiveness often rest on instructor testimonials, student satisfaction surveys, or small-scale quasi-experimental studies rather than robust longitudinal analysis.
- **Uneven Adoption and Implementation:** Many documented innovations never diffuse beyond originating institutions or revert to traditional formats after initial implementation. Literature rarely examines why some reforms scale successfully while others remain isolated experiments, nor does it adequately analyze institutional, political, and resource factors shaping adoption.
- **Tension Between Mathematical Rigor and Engineering Utility:** While literature acknowledges debates about appropriate mathematical depth for engineers, it lacks consensus on optimal balance. Should engineers master theoretical foundations even when computational tools handle calculations? What level of mathematical sophistication sufficiently prepares graduates for lifelong learning and professional adaptation? These questions remain contested.
- **Inadequate Attention to Faculty Development:** Designing and teaching integrated, computationally-oriented, application-rich mathematics courses requires instructors with expertise spanning mathematics, engineering, and pedagogy—yet literature offers limited guidance on how to develop such capacity at scale. Faculty training, professional development, and support structures receive insufficient attention.
- **Limited Global Perspective:** Most literature focuses on North American and European contexts. Given engineering education's global nature, comparative international studies examining how local contexts shape mathematics curricula would enhance understanding and identify alternative models.
- **Emerging Domains Remain Under-Researched:** Data science, artificial intelligence, machine learning, computational modeling, and uncertainty quantification appear increasingly in engineering practice, yet systematic integration into foundational mathematics curricula remains nascent and poorly documented. How should traditional calculus-based sequences adapt to these new demands?
- **Structural and Systems Perspectives are Underdeveloped:** Only recently have researchers examined engineering curricula as complex systems, analyzing how course prerequisite structures, sequencing decisions, and degree requirements shape student progression. More systems-level analysis could identify intervention leverage points beyond individual course redesign.

These gaps suggest substantial opportunities for rigorous empirical research employing archival analysis, multi-institution datasets, longitudinal tracking, and sophisticated quantitative methods to understand engineering mathematics education evolution and effectiveness.

RECOMMENDATIONS FOR FUTURE RESEARCH

A systematic research program addressing identified gaps should pursue several complementary strategies:

- **Build comprehensive longitudinal datasets:** Collect mathematics curriculum data (course titles, credits, prerequisites, content) across multiple institutions and decades using archived course catalogs, syllabi, textbooks, and ABET program reports. Such datasets would enable systematic analysis of trends, diffusion patterns, and correlates of curricular change.
- **Develop detailed qualitative curriculum profiles:** Supplement quantitative data with qualitative analysis of syllabi content, assigned textbooks, pedagogical approaches (lecture vs. active learning), technology integration (computational labs, software requirements), and assessment methods. Course titles alone inadequately capture actual content and pedagogy.
- **Link curricula to student outcomes:** Merge curriculum data with student-level outcomes (retention, course grades, graduation rates, time-to-degree, major switching, post-graduation employment and earnings) to assess how different mathematics curriculum structures and contents affect student success. Such analysis requires institutional research office partnerships and appropriate privacy protections.
- **Investigate faculty capacity and professional development:** Survey and interview faculty teaching engineering mathematics to understand training backgrounds, professional development experiences, pedagogical beliefs, resource needs, and barriers to innovation. How do institutions successfully develop and sustain faculty capable of teaching integrated, computationally-oriented mathematics?
- **Conduct comparative studies across engineering disciplines:** Examine whether mathematics curriculum evolution differs across engineering disciplines (electrical vs. mechanical vs. civil vs. chemical vs. software engineering) and whether discipline-specific mathematics tracks better serve students than common core sequences.
- **Expand international and cross-cultural research:** Include institutions beyond North America and Europe to understand how national education systems, cultural factors, resource constraints, and engineering labor markets shape mathematics curricula. What can U.S. engineering programs learn from alternative international models?
- **Develop predictive models of curriculum effectiveness:** Move beyond descriptive analysis toward predictive models identifying which curriculum features (content, sequencing, pedagogy, technology integration) most strongly predict desired outcomes for different student populations. Such models could guide evidence-based curriculum design.
- **Create “living” curriculum databases:** Establish continuously-updated repositories documenting engineering mathematics curricula evolution, emerging practices, and evaluation results—analogous to systematic review databases in medicine. Such infrastructure could accelerate knowledge accumulation and evidence-based practice.
- **Study implementation science and change processes:** Investigate why some reforms diffuse widely while others remain isolated, examining institutional conditions, change processes, leadership factors, and sustainability mechanisms. What organizational structures, incentives, and resources enable successful curriculum transformation?
- **Assess emerging competencies and future needs:** Develop frameworks for mathematical competencies engineers will need as practice continues evolving (data science, AI, uncertainty quantification, computational modeling) and evaluate whether current curricula adequately prepare students for these emerging demands.

Toward a Framework for Future Engineering Mathematics Curricula

The accumulated evidence reviewed in this paper — spanning six decades of historical development, contemporary empirical research on student learning and motivation, large-scale institutional data on academic performance, and systematic international literature synthesis — points toward a coherent set of principles for future engineering mathematics curriculum design. This section draws these threads together into a preliminary framework, informed particularly by the international comparative perspective of Pepin et al. (2021) and the competency-based orientation of SEFI (2013), situating them within the specific institutional and outcome evidence developed in the preceding sections.

Principle 1: Organize Around Competencies, Not Topics: Future engineering mathematics curricula should be organized primarily around mathematical competencies — what students can do with mathematics — rather than topics to be covered. The SEFI (2013) framework, grounded in Niss’s (2003) competency model, provides a research-validated starting point: its eight competencies (mathematical thinking, reasoning, problem posing and solving, modelling, representing, symbolic handling, communicating, and tool use) map far more directly onto engineering practice than topic inventories. A competency orientation also provides clearer guidance for assessment design: rather than testing recall of procedures, assessments can evaluate whether students can apply mathematical reasoning in novel engineering contexts, construct models from physical descriptions, interpret computational results critically, or communicate mathematical arguments to non-specialist audiences. This shift would directly address Faulkner et al.’s (2019) finding that engineering faculty expect mathematical maturity from graduates yet receive students trained almost exclusively for procedural performance.

Principle 2: Integrate Engineering Context from the Outset: Mathematics instruction for engineers should embed engineering applications throughout, not as terminal illustrations of abstract content but as the primary motivating context from which mathematical concepts are developed and into which they are applied. The evidence for this principle is consistent across methodological traditions: Goold's (2014) qualitative study showed that students' utility value for mathematics increased dramatically when they encountered it in professional engineering contexts; Wolf's (2017) curriculum experiments demonstrated that modelling tasks from mechanical engineering contexts improved motivation and engagement; Whitcomb et al.'s (2020) large-scale regression data show that students who understood foundational mathematics at deeper levels transferred it more effectively to subsequent engineering courses; and Meyer and Fang's (2019) departure narratives reveal that students who left engineering frequently cited an inability to perceive mathematics' relevance as a contributing factor. Pepin et al. (2021) confirm this as an international pattern, noting that engineering students consistently drew on mathematics for its use-value and exchange-value rather than its intrinsic mathematical interest — a motivation structure that curriculum designers should work with rather than against.

Principle 3: Treat Computation as Integral, Not Supplemental: As argued by Grizzle (2025), Kamalov and Leung (2022), and the broader trajectory of the field, computational thinking and digital tool use should be woven throughout engineering mathematics from the first week of instruction rather than confined to specialized computational labs or upper-division electives. This means more than adding MATLAB exercises to calculus courses: it means reconceptualizing which mathematical content matters when students have access to symbolic computation systems, teaching numerical and analytical methods in parallel rather than sequentially, and developing the critical-interpretive competencies that Pepin et al. (2021) identify under the heading of techno-mathematical literacies. Kiianovska et al.'s (2018) six-stage ICT adoption trajectory suggests that this evolution is already well advanced at leading institutions; the challenge for curriculum designers is to ensure that computational integration supports genuine mathematical understanding rather than bypassing it. Dana-Picard and Steiner's (2004) recommendation for 'low-level' CAS commands that make computational processes visible to students rather than obscuring them in black-box automation remains an important design heuristic in this regard.

Principle 4: Actively Develop Mathematical Identity and Self-Efficacy: Curriculum frameworks must explicitly address the affective and identity dimensions of mathematical learning, not leave them to chance. The international evidence reviewed by Pepin et al. (2021) — including Kaspersen et al.'s (2017) finding that mathematical identity predicts grades independently of ability, and Kürten's (2017) demonstration that bridging courses can produce durable self-efficacy gains — converges with the domestic evidence reviewed in section 9.1 and 9.2 to suggest that students' beliefs about themselves as mathematical learners are genuinely consequential for outcomes. Curriculum frameworks should therefore include explicit mechanisms for identity-supportive instruction: authentic engineering applications that signal mathematics' value in professional contexts; early success experiences designed to build competency beliefs; social learning environments that normalize mathematical struggle and collaborative problem-solving; and transition support programs that prepare students for the qualitative discontinuity between secondary and university mathematics. Kenyon and Benson's (2025) finding that explicit communication of assessment purpose can shift students toward more productive exam perceptions is a specific, actionable example of how identity-supporting curriculum design might work in practice.

Principle 5: Align Assessment with Competencies and Learning: Assessment reform is not peripheral to curriculum innovation but central to it. The consistent evidence across studies — from Wolf (2017) in Germany to Kenyon and Benson (2025) in the United States to Pepin et al.'s (2021) international synthesis — is that innovative pedagogical practices fail to produce durable learning gains when examination systems continue to reward only procedural performance. Future curriculum frameworks should therefore design assessment systems that evaluate the same competencies that instruction develops: mathematical modelling, contextual problem-solving, computational reasoning, and mathematical communication. Formative assessment — weekly quizzes, reflective assignments, error-correction opportunities, peer assessment — should complement rather than merely precede summative examinations. High-stakes single-examination structures should be examined critically in light of their demonstrated contribution to math test anxiety, contingent-goal fragility, and inequitable outcomes for financially vulnerable students (Kenyon & Benson, 2025).

Principle 6: Build Institutional Infrastructure for Sustained Reform: No curriculum framework can succeed without the institutional conditions that enable and sustain it. Pepin et al.'s (2021) comparative institutional case study, examining why engineering calculus reform persisted in one institution but not another, found that successful sustained reform required: an interdepartmentally embedded and respected coordinator; systematic professional development for instructors; measurable success indicators; and sustained communication and shared vision among stakeholders. These findings echo the institutional analysis in section 9.5 of this review, which identified faculty capacity, departmental structure, resource constraints, risk aversion, and assessment challenges as the primary barriers to implementation. The implication is that future curriculum reform efforts must be designed as institutional change projects, not merely as pedagogical innovations — with explicit attention to change management, coalition building, resource allocation, and sustainability mechanisms from the outset (Borrego & Henderson, 2014; Kezar, 2018).

Taken together, these six principles constitute not a detailed curriculum prescription but a framework of orientations that can guide diverse institutions in designing engineering mathematics curricula appropriate to their contexts, student populations, and disciplinary cultures. The principles are mutually reinforcing: a competency orientation makes assessment reform more tractable; computational integration creates natural opportunities for modelling; identity-supportive instruction increases engagement with context-rich tasks; and institutional infrastructure sustains all the other dimensions over time. Realizing this framework at scale will require the sustained, systematic, and collaborative research infrastructure that sections 11 and 12 of this review call for — research that spans institutions, disciplines, and decades, and that takes both the pedagogical complexity and the institutional reality of engineering mathematics education.

CONCLUSION

From mid-century applied analysis and numerical methods textbooks to contemporary data-science-enabled, computation-rich, context-integrated engineering mathematics courses, the field has undergone a profound transformation. Mathematics for engineers has evolved from a gate-keeping prerequisite toward a dynamic, integrated component of engineering professional identity and practice—though this evolution has been uneven, contested, and institutionally heterogeneous.

The literature provides rich case studies, thoughtful theoretical reflection, and increasingly sophisticated empirical analysis. However, systematic, large-scale, longitudinal perspectives remain underdeveloped. We lack a comprehensive understanding of how mathematics curricula have evolved across the engineering education landscape, which reforms have proven effective and sustainable, what barriers impede adoption of promising practices, and how mathematics education should adapt to emerging engineering paradigms centered on data, computation, and artificial intelligence.

Addressing these gaps requires sustained, systematic empirical research combining quantitative longitudinal analysis, detailed qualitative curriculum study, rigorous outcome assessment, and implementation science perspectives. Such research would not only document historical evolution but provide evidence-based guidance for future curriculum development—helping ensure that mathematics education continues evolving to meet the changing needs of engineering students, the profession, and society.

The transformation of engineering mathematics education over the past six decades demonstrates both the field's capacity for significant change and the persistent challenges that accompany such evolution. As engineering practice continues transforming in response to technological advancement and societal needs, mathematics education must likewise continue adapting—informed by rigorous research, guided by evidence, and grounded in a deep understanding of how students learn, how engineers work, and how institutions change.

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