A Scoping Review of Adaptive Learning Systems in Engineering Education

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1. Introduction

Engineering education continues to face persistent challenges related to learner diversity, scalability of instruction, and gaps in conceptual understanding, particularly in large-enrollment foundational courses. Engineering students enter programs with widely varying levels of prior knowledge, cognitive preparedness, motivation, and learning strategies, yet instructional approaches often remain uniform in pacing, content sequencing, assessment structure, and feedback delivery, and are constrained by limited instructional time. This mismatch has been linked to high attrition rates, persistent misconceptions, and inequities in student outcomes across engineering disciplines [1, 2]. Addressing these challenges requires instructional approaches that can respond dynamically to individual learner needs while remaining scalable within institutional constraints.

Adaptive learning systems (ALS) have emerged as a promising response to these challenges. Broadly defined, ALS are technology-enhanced learning environments that adapt instructional content, feedback, assessment, or pacing based on data about learners' performance, behaviors, or inferred cognitive states [3, 4]. Rooted in earlier work on intelligent tutoring systems and adaptive hypermedia, ALS aim to approximate the benefits of one-to-one tutoring by providing personalized instructional support at scale [5, 6]. Meta-analyses and reviews demonstrate that such systems can produce learning gains comparable to human tutoring across structured problem domains [7, 8].

Within engineering education, adaptive learning systems have been increasingly adopted in gateway courses such as circuits, programming, statics, and mechanics, where cumulative knowledge structures and well-defined problem spaces make adaptive assessment and feedback particularly well suited [1]. Prior studies report positive outcomes associated with adaptive systems in engineering contexts, including improved performance, increased engagement, and more efficient instructional support [9, 10]. However, despite growing interest, research on adaptive learning systems in engineering education remains fragmented. Existing studies vary widely in how adaptivity is conceptualized, what instructional elements are adapted, how systems are evaluated, and the extent to which methodological rigor and ethical considerations are addressed.

Recent critiques of AI-enabled educational technologies further highlight the need for greater transparency, theoretical grounding, and ethical responsibility in adaptive learning research [11, 12]. Issues related to algorithmic opacity, data privacy, learner agency, and equity are particularly salient in engineering education, where adaptive systems may influence high-stakes outcomes such as course progression and retention. Yet these issues are often underreported or inconsistently addressed in adaptive learning system research, complicating efforts to synthesize evidence and inform practice.

Scoping reviews are well suited to examining such emerging and heterogeneous bodies of research. Unlike systematic reviews focused on narrowly defined effectiveness questions, scoping reviews aim to map the breadth, characteristics, and conceptual foundations of a research area and identify gaps to guide future inquiry [13, 14]. Accordingly, this Work-in-Progress scoping review seeks to map the landscape of adaptive learning systems in engineering education, focusing on how systems are conceptualized and designed, the instructional contexts in which they are deployed, the learning outcomes they target, and the methodological and ethical considerations shaping existing research.

This study is guided by the following research questions:

- **RQ1:** How are adaptive learning systems conceptualized, designed, and implemented in engineering education?
- **RQ2:** What types of learning outcomes and pedagogical outcomes are reported from the use of adaptive learning systems?
- **RQ3:** What methodological and ethical considerations emerge in existing adaptive learning system research within engineering contexts?

2. Methods

2.1 Scoping Review Design

This study employs a scoping review methodology to map the landscape of adaptive learning systems in engineering education. A scoping review was selected over a systematic review or meta-analysis because the body of research on adaptive learning systems in engineering education is conceptually heterogeneous, methodologically diverse, and still emerging. Existing studies vary widely in how adaptivity is defined and operationalized, the instructional elements targeted for adaptation, the learning contexts examined, and the outcomes reported. These characteristics make quantitative synthesis or effect-size aggregation premature. Scoping reviews are specifically designed to map such fragmented literatures, clarify conceptual boundaries, and identify dominant research patterns and gaps rather than to evaluate intervention effectiveness [13, 14]. Given the exploratory state of adaptive learning research in engineering education, a scoping review provides the most appropriate methodological approach for establishing an evidence-informed foundation to guide future empirical and evaluative studies. The review follows the five-stage framework proposed by Arksey and O'Malley [13] and is reported in accordance with the PRISMA Extension for Scoping Reviews [15].

Consistent with scoping review methodology, this review includes both engineering-specific studies and foundational, domain-agnostic educational technology research that informs the design and application of adaptive learning systems in engineering education. Such work particularly research on learner modeling, adaptive system architectures, and instructional adaptation, is frequently cited and adopted within engineering education and therefore constitutes an essential part of the knowledge base shaping adaptive learning system development in engineering contexts [3, 4]. Consistent with the Work-in-Progress nature of this study, data extraction and synthesis are ongoing at the time of reporting.

2.2 Search Strategy

A comprehensive literature search was conducted across seven major databases relevant to engineering and education research: Web of Science, ERIC (via EBSCOhost), IEEE Xplore, Education Research Complete, APA PsycINFO, Engineering Village, and ScienceDirect. These databases were selected to ensure broad coverage of both engineering education scholarship and technically oriented research on adaptive and intelligent learning systems.

The search strategy was designed to support the full scoping review and subsequent journal publication. Search terms were organized around two conceptual blocks: (1) adaptive and personalized learning systems and (2) engineering education contexts. Boolean operators were used to combine synonymous terms within each block, and search strings were adapted to the syntax and indexing conventions of each database. Key search terms included combinations of *adaptive learning*, *adaptive learning systems*, *personalized instruction*, *intelligent tutoring systems*, *adaptive assessment*, and *engineering education*.

The search included peer-reviewed journal articles and conference papers published in English between January 1, 2005, and December 31, 2024, capturing both foundational work on intelligent tutoring systems and more recent AI-driven adaptive learning approaches in engineering education as shown in Table1 below. All records retrieved represent initial results prior to duplicate removal and screening.

Table 1. Databases searched and initial record counts

Database	Records Retrieved
ERIC (via EBSCOhost)	167
Web of Science	224
IEEE Xplore	298
ScienceDirect	500
Education Research Complete	237
Computer Science Database	925
Engineering Village	2,293
Total	4,644

2.3 Study Selection

All retrieved records were imported into Rayyan, a web-based tool for systematic review management, for duplicate removal and screening [16]. Titles and abstracts were screened by one reviewer against predefined inclusion criteria. Studies were included if they: (a) examined adaptive learning systems, (b) were situated within engineering or closely related computing education contexts, and (c) reported on system design, implementation, or evaluation. Studies focused exclusively on K–12 contexts, non-adaptive instructional technologies, or non-engineering domains were excluded. Full-text screening is currently underway. Given the Work-in-Progress status of this review, inclusion and exclusion decisions continue to be refined through team discussion to ensure conceptual consistency with the review's scope.

2.4 Data Charting and Coding (Work-in-Progress)

Data charting is being conducted using a structured coding framework developed iteratively by the research team. A preliminary codebook guides extraction of information related to publication characteristics, engineering discipline, instructional level, adaptive mechanisms (e.g., rule-based, learner-model-driven, or machine-learning-based), targets of adaptation (e.g., feedback, assessment, content sequencing), reported learning outcomes, and methodological features.

Coding is currently ongoing using Microsoft Excel. To enhance reliability, multiple reviewers are independently coding a subset of studies, with discrepancies discussed to refine code definitions and improve consistency. Formal inter-rater agreement analysis will be conducted upon completion of data extraction. Consistent with the Work-in-Progress intent, this paper seeks feedback on the proposed coding framework and data charting approach prior to final synthesis.

3. Preliminary Results and Observations

This section reports preliminary, descriptive findings from the ongoing review. At the time of writing, 75 full-text articles have been screened, of which 16 studies meet the inclusion criteria and have been fully coded, reflecting the early stage of data extraction and synthesis. The results presented here reflect early patterns and distributions observed in the coded studies and are intended to support mapping of the research landscape rather than definitive conclusions. Consistent with the purpose of a scoping review, results are organized thematically around the study's research questions to highlight dominant patterns and gaps. All findings should therefore be interpreted as illustrative and subject to refinement as coding continues.

3.1 Instructional and Disciplinary Contexts

Analysis of the coded studies (n = 16) indicates that adaptive learning systems are examined across a diverse set of instructional contexts relevant to engineering education, including engineering-specific courses, engineering-adjacent computing disciplines, and domain-agnostic educational technology research as shown in Table2.

As summarized in Table 2, the coded corpus includes studies situated within engineering programs, programming and computer science contexts commonly housed in engineering faculties, and domain-agnostic adaptive learning research. The latter category refers to studies that examine adaptive learning system design and functionality without being tied to a specific disciplinary subject, such as work on adaptive system architectures, learner modeling, or instructional frameworks [17, 18]. These studies are frequently cited within engineering education literature and provide foundational insights that inform the design of adaptive systems later applied in engineering contexts.

Importantly, among the engineering-specific studies, each is situated in a distinct course context, including electric circuits, engineering mathematics, engineering design, and flipped undergraduate engineering courses [19, 20]. In several cases, studies are conducted within engineering programs without explicitly specifying a single disciplinary focus. No engineering sub-discipline is represented by more than one study, indicating that adaptive learning research informing engineering education is currently distributed across isolated course contexts rather than concentrated within a single discipline or organized around a unified curricular focus.

3.2 Adaptive Mechanisms Employed

Preliminary coding of the studies (n = 16) indicates that adaptive learning systems relevant to engineering education employ a range of adaptation mechanisms, with a strong emphasis on rule-based and learner-model-driven approaches. These mechanisms typically operationalize adaptivity through predefined decision rules, mastery thresholds, or inferred learner knowledge states that guide instructional feedback, sequencing, or progression [17, 21, 22].

As shown in Figure 1, rule-based or heuristic adaptation represents the most common approach, followed by learner-model-driven systems that adapt instruction based on representations of learner knowledge or performance. Several studies adopt pedagogical adaptation strategies that adjust instructional support or learning activities without relying on explicit algorithmic models [19, 20]. A small number of studies employ more advanced data-driven techniques, including fuzzy-logic-based adaptation and large language model (LLM)-based adaptation, reflecting emerging interest in AI-enabled adaptivity [23, 24].

Overall, the distribution of adaptive mechanisms suggests that research informing engineering education continues to favor interpretable and deterministic adaptation strategies, particularly those aligned with structured problem domains and mastery-oriented learning goals. More computationally intensive or opaque approaches remain relatively uncommon in the coded literature, indicating that the adoption of advanced AI-driven adaptivity in engineering education is still at an early stage.

Table 2. Instructional and disciplinary contexts of coded studies (n = 16)

Context category	Count
General educational technology (non-discipline-specific)	7
Programming / computer science / information systems	2
Engineering-specific contexts (e.g., circuits, engineering mathematics, design, flipped engineering courses)	7

3.3 Targets of Adaptation

In addition to identifying adaptive mechanisms, the coded studies (n = 16) were examined to determine which instructional elements were targeted for adaptation. Because many adaptive learning systems address multiple instructional components simultaneously, individual studies were permitted to be coded into more than one adaptation target category.

As summarized in Table 3, adaptation most frequently targets assessment, content sequencing, and feedback, reflecting a strong emphasis on individualized practice and formative assessment support. Assessment-focused adaptation often involves mastery-based quizzes, diagnostic testing, or adaptive problem selection [17, 22, 25]. Content sequencing adaptations typically personalize learning pathways or adjust the order of instructional materials based on learner performance or inferred knowledge states [18, 21]. Feedback and guidance adaptations commonly provide hints, explanations, or error-specific feedback tailored to learner responses [19, 20].

Adaptation targeting pacing, such as allowing learners to progress through content at variable rates based on mastery is also evident across studies, though less consistently emphasized than assessment or sequencing. In contrast, relatively few studies incorporate user interface adaptation, and none of the coded studies explicitly focus on adaptive support for collaborative or group-based learning. Collectively, these patterns suggest that adaptive learning systems informing engineering education are most often conceptualized as extensions of formative assessment and individualized learning pathways, rather than as comprehensive environments that adapt social or collaborative dimensions of learning.

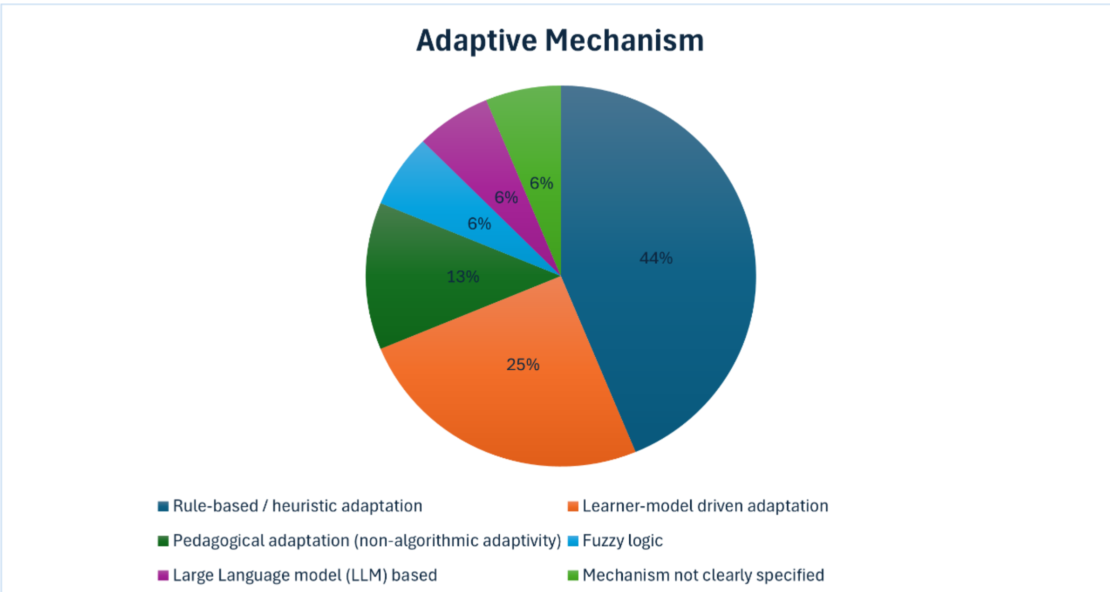

Figure 1: Distribution of Adaptive mechanisms identified across the coded studies.

Table 3. Targets of adaptation across coded studies

Target of adaptation	Count
Assessment	13
Content sequencing	12
Feedback / guidance	10
Pacing	10
User interface adaptation	5

3.4 Reported Outcomes and Research Designs

Across the coded studies (n = 16), reported outcomes are predominantly short-term and course-level in nature. Six studies report performance-related outcomes, such as assessment scores, task completion, or mastery progression within adaptive systems [19, 22, 25]. Eight studies report learner perception outcomes, including perceived usefulness, usability, or satisfaction with adaptive learning environments [20, 21, 26]. Measures related to learner engagement or behavioral patterns such as time-on-task, navigation behavior, or progression through adaptive content are reported in five studies [17, 18, 23].

Only two studies examine outcomes extending beyond a single instructional unit or short intervention period [20, 24], and just one study reports learning outcomes situated within a clearly identified engineering discipline [19]. Longitudinal learning outcomes, transfer of knowledge, or persistence-related measures are rarely examined in the coded literature.

With respect to research design, descriptive and quasi-experimental approaches are most common, appearing in nine of the 16 studies [21, 22, 27]. Design-based research approaches are reported in four studies, typically alongside iterative system development and refinement [17, 18]. More rigorous experimental designs are comparatively rare: only one study adopts a longitudinal evaluation perspective [24], and fully randomized controlled trials are not observed in the coded corpus.

3.5 Methodological and Ethical Considerations

Analysis of the coded studies (n = 16) indicates substantial variation in methodological emphasis across adaptive learning research relevant to engineering education. Ten of the 16 studies primarily focus on system design, architectural frameworks, or prototype development, with limited empirical evaluation beyond feasibility or usability testing [17, 18, 21, 22]. These studies emphasize conceptualizing adaptivity, learner modeling, or sequencing logic rather than examining learning outcomes in sustained instructional settings.

The remaining six studies report some form of empirical evaluation; however, these evaluations are typically short-term and context-specific, relying on descriptive or quasi-experimental designs. Outcome measures most often include learner performance, progression through adaptive content, or learner perceptions of usefulness and usability [19, 20, 25]. Only one study explicitly evaluates an adaptive learning system within a named engineering discipline and an authentic engineering course context [19].

Ethical and transparency considerations are reported inconsistently across the coded literature. Only three of the 16 studies explicitly discuss issues related to data privacy, learner consent, or responsible system use [24, 28, 29], while the remaining studies provide little to no discussion of algorithmic transparency, learner agency, data governance, or equity-related considerations.

Discussion

This Work-in-Progress scoping review provides an initial synthesis of how adaptive learning systems are conceptualized, designed, implemented, and studied within engineering education and related domains. Drawing on preliminary analysis of 16 coded studies, the findings reveal a research landscape characterized by contextual diversity, design-driven innovation, and uneven methodological and ethical articulation. Rather than a cohesive, discipline-centered body of evidence, the literature reflects a fragmented ecosystem in which adaptive learning research informs engineering education through a mix of engineering-specific applications, engineering-adjacent computing contexts, and domain-agnostic educational technology studies.

A key pattern emerging from the results is the localized and course-level nature of adaptive learning system implementation in engineering education. Engineering-specific studies are dispersed across distinct instructional contexts such as electric circuits, engineering mathematics, engineering design, and flipped undergraduate courses without concentration in any single sub-discipline (e.g.,[19, 20].This dispersion suggests that adaptive learning adoption is largely driven by immediate instructional needs rather than coordinated curricular strategies. For engineering education research, this indicates a need to move beyond isolated course implementations toward programmatic and cross-course investigations that examine how adaptive learning systems can support conceptual development across sequences of foundational engineering courses. At the same time, the inclusion of domain-agnostic studies [17, 18, 21] highlights the extent to which engineering education continues to draw on foundational adaptive learning research developed outside explicitly engineering contexts.

Across the coded studies, adaptive learning systems are most frequently designed using rule-based and learner-model-driven mechanisms, consistent with foundational work in adaptive learning and intelligent tutoring systems [3-5, 7]. Many systems operationalize adaptivity through mastery thresholds, predefined rules, or inferred knowledge states [17, 21, 22], reflecting a preference for interpretable and deterministic approaches aligned with structured engineering problem domains. For engineering education researchers, this pattern suggests that adaptivity is often treated as a technical mechanism rather than a pedagogical construct, underscoring the need for theory-driven studies that examine how specific adaptive designs support engineering learning processes such as conceptual change, problem solving, and transfer. "More advanced AI-driven approaches, such as fuzzy logic or large language model–based adaptation, appear only in a small number of recent studies [23, 24], indicating that such techniques remain emergent in engineering education contexts; recent work in computing education also reflects this trend through GenAI-supported environments that provide personalized hints and adaptive real-time support [30].

In terms of instructional focus and outcomes, the literature overwhelmingly frames adaptive learning systems as mechanisms for supporting formative assessment, individualized practice, and content sequencing. Most studies report short-term outcomes related to performance, system use, or learner perceptions [21, 25, 26], with limited attention to longitudinal learning, transfer, or persistence. Only one study situates outcomes explicitly within a named engineering discipline and authentic course context [19]. This emphasis has important implications for engineering education research, suggesting that future studies should extend evaluation beyond immediate course outcomes to examine how adaptive learning influences longer-term learning trajectories, retention, and equity across engineering programs. This pattern mirrors broader critiques in adaptive learning research regarding limited empirical depth [7, 8].

Methodological and ethical considerations further underscore the early-stage nature of adaptive learning research informing engineering education. Many studies prioritize system design and prototype development over rigorous empirical evaluation [18], and ethical issues such as data privacy, learner agency, and algorithmic transparency are addressed inconsistently. Only a small subset of studies explicitly engages with these concerns [24, 28, 29] echoing wider calls for more responsible and transparent use of AI-enabled educational technologies [11]. For engineering education practice, this highlights the importance of integrating ethical and methodological considerations into adaptive learning research from the outset, particularly given the high-stakes instructional decisions adaptive systems may influence in engineering programs. Collectively, these findings suggest that while adaptive learning systems show promise for addressing scalability and personalization challenges in engineering education, sustained progress will depend on more coordinated, theoretically grounded, and ethically informed research efforts.

Conclusion

This Work-in-Progress paper reports the initial phase of an ongoing scoping review of adaptive learning systems in engineering education. At this stage, the study has established the review scope, search strategy, and analytic framework, and has begun systematic coding of the identified literature. Preliminary analysis of the coded studies suggests that adaptive learning systems informing engineering education are most commonly implemented at the course level, rely primarily on rule-based or learner-model-driven adaptation, and focus on formative assessment, feedback, and content sequencing, with limited attention to longitudinal outcomes or ethical considerations. Ongoing work will complete full-text screening and data extraction across the full corpus of studies, refine the coding scheme through iterative team discussion, and enable a more comprehensive synthesis of adaptive learning system designs, instructional contexts, reported outcomes, and methodological and ethical considerations. As the review progresses, the expanded synthesis is expected to clarify dominant patterns and gaps in how adaptive learning systems are conceptualized and evaluated in engineering education and to support the development of an evidence-informed research agenda to guide future adaptive learning design and implementation efforts.

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