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ADAPTIVE CURRICULUM DESIGN FOR TECHNICAL SYSTEMS INSTRUCTION: A MULTILEVEL HIERARCHICAL FRAMEWORK BASED ON AI-ASSISTED LEARNING PATHWAYS

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Abstract

Engineering education faces a structural tension: the need to develop students' systems-level reasoning about complex technical objects conflicts with the wide variance in students' prior knowledge, cognitive readiness, and disciplinary background. Standard fixed-sequence curricula address neither the breadth of the hierarchy students must traverse nor the individual variation in how they traverse it.

AI-assisted diagnosis tools - including knowledge space theory-based assessment, Bayesian student modelling, and natural language interaction through large language model tutors - are proposed as the mechanism for adaptive pathway assignment and transition. The paper analyses the theoretical foundations of each adaptive mechanism, maps them to specific hierarchical instructional stages, and provides curriculum design guidelines for engineering faculty.

Keywords: Adaptive curriculum, hierarchical instruction, technical systems, AI-assisted learning, Bayesian student modelling, knowledge space theory, engineering education, learning pathway, multilevel framework.

Introduction

Two structural facts define the instructional challenge of teaching technical systems in engineering programmes. The first is cognitive: understanding a complex technical system - a power plant, an industrial robot, or an automated conveyor line - requires simultaneously managing knowledge at multiple levels of abstraction, from physical component behaviour to system-wide control logic. The second is pedagogical: students entering advanced engineering courses arrive with widely heterogeneous prior knowledge profiles, ranging from those who have substantial hands-on experience with technical components to those whose exposure to hardware is almost entirely theoretical.

Fixed-sequence curricula address neither challenge adequately. They impose a single pace and a single level of abstraction on all learners simultaneously, producing two well-documented failure modes: cognitive overload in underprepared students exposed prematurely to system-level complexity, and intellectual disengagement in well-prepared students forced to revisit already-mastered component-level material. Adaptive learning systems - which diagnose each student's current knowledge state and route them through personalised instructional sequences - are the pedagogically principled response to this heterogeneity.

Theoretical foundations

Mesarovic's multilevel systems theory provides the structural taxonomy of the technical knowledge domain that the adaptive framework must navigate. What the adaptive system must diagnose at each level is not simply whether the student knows the relevant facts, but whether they have achieved functional competency - the ability to build, operate, and interpret models at that level - sufficient to serve as a cognitive foundation for the next level. This distinction, between declarative knowledge and procedural-functional competency, is critical to adaptive pathway design in engineering education.

Bloom's revised taxonomy (Anderson & Krathwohl, 2001) provides the competency dimension along which adaptation operates at each hierarchical level: at any given level, a student may be operating at the remembering/understanding sub-level (knowing what the elements are), the applying/analysing sub-level (being able to use and decompose the elements), or the evaluating/creating sub-level (being able to assess and design at that level). The adaptive system assigns each student to one of these sub-levels at each hierarchical stage and adjusts the instructional pathway accordingly.

Diagnostic Mechanisms. Three AI-assisted diagnostic mechanisms are proposed as the assessment engine of the adaptive framework. The first is Knowledge Space Theory (KST)-based assessment: KST, developed by Doignon and Falmagne, models the space of possible knowledge states as a partially ordered set and diagnoses the student's current state through an adaptive questioning procedure. For hierarchical technical systems instruction, the knowledge space is structured around the partial order of the Mesarovic levels: competency at Level I is a prerequisite for meaningful competency at Level II, and so forth. KST-based assessment can pinpoint a student's position in this space after a small number of diagnostic questions, enabling rapid pathway assignment.

The second mechanism is Bayesian student modelling: a Bayesian network maintains a dynamic probabilistic estimate of each student's competency at each hierarchical level, updated continuously as the student completes formative tasks and interacts with the simulation environment. The network's conditional probability structure encodes the hierarchical dependency between levels, so that strong performance at Level I raises the prior probability of competency at Level

II. This enables the adaptive system to anticipate needed scaffolding before a student encounters explicit difficulty.

The third mechanism is large language model (LLM) tutoring: AI-powered conversational tutors, deployed within the learning management system, can conduct Socratic dialogue sequences that probe the student's conceptual model of a technical system and identify misconceptions at specific hierarchical levels. Unlike static diagnostic tests, LLM tutors can respond to the student's reasoning in real time, identifying not just what the student does not know but the specific logical gap that prevents them from moving to the next hierarchical level.

Four adaptive pathways: design and transitions. Pathway Typology. Based on the initial KST diagnostic and the first two weeks' Bayesian model updates, each student is assigned to one of four adaptive pathways. The pathways are not fixed categories but dynamic attractors: a student's pathway assignment is reviewed at each hierarchical transition point, and movement between pathways is routine rather than exceptional. The pathways are defined by three parameters: depth of component-level treatment, degree of scaffolding provided at each level, and pace of hierarchical progression.

Pathway Transition Logic. Transition between hierarchical levels - and between pathways - is governed by a competency threshold criterion rather than a calendar criterion. A student transitions from Level I to Level II instruction when their Bayesian competency estimate at Level I exceeds a defined threshold (set at 0.75 probability of functional competency in the proposed model), validated by a practical simulation task. This criterion can be met at different calendar points by different students, decoupling hierarchical progression from the fixed weekly schedule.

Students on the Accelerated pathway may reach Level IV (full system instruction) as early as Week 10, at which point they engage with extension tasks - independent DT scenario design, reverse engineering of industrial systems, or peer instruction - rather than waiting for the standard cohort. Students on the Scaffolded pathway may reach Level IV as late as Week 15; the final assessment is held in Week 16 regardless of pathway, ensuring summative equity while accommodating individual trajectories.

Adaptive curriculum design framework: implementation guidelines. The adaptive curriculum design framework is structured around five implementation principles derived from the theoretical analysis and the pathway typology:

1. Hierarchy-first structure: the curriculum's macro-structure is defined by the four hierarchical levels, not by topic coverage. Each course module maps to a specific level, and the level sequence is invariant across pathways even as the depth and pace vary.
2. Competency gateway assessment: each hierarchical transition is gated by a practical competency assessment (simulation task + LLM tutor dialogue) rather than a written test alone. This ensures that the pathway system responds to functional competency, not to declarative recall.
3. Visible hierarchy: students are explicitly taught the four-level framework at the course outset and can always see their current position within it on the LMS dashboard. Metacognitive awareness of one's own position in the hierarchy is itself a component of systems thinking .
4. Instructor-AI collaboration: the adaptive pathway system provides instructors with a real-time dashboard displaying the distribution of students across pathways and hierarchical levels. Instructors retain authority over pathway reassignment

and can override algorithmic decisions - the AI system augments rather than replaces pedagogical judgement.

5. Formative feedback density: each hierarchical level includes at least three formative assessment events (simulation task, LLM dialogue, peer review) before the gateway competency assessment. Hattie and Timperley's (2007) model of feedback typology informs the design of each event: simulation tasks provide task-level feedback, LLM dialogues provide process-level feedback, and peer review provides self-regulation-level feedback.

Conclusion

This paper has presented an adaptive curriculum design framework for technical systems instruction grounded in hierarchical systems theory and implemented through AI-assisted learning pathway management. The framework's principal theoretical contribution is the integration of Mesarovic's multilevel hierarchy as the structural backbone of an adaptive curriculum - ensuring that all students traverse the complete hierarchy while accommodating individual differences in pace, depth, and scaffolding requirements.

Three conclusions are drawn for engineering curriculum designers:

1. Adaptive learning in technical systems instruction is most effective when the adaptive variable is hierarchical competency, not topic coverage. Diagnosing where in the four-level hierarchy a student is currently operating - and what prevents them from advancing - is more pedagogically actionable than measuring aggregate course performance.

2. AI diagnostic tools - KST-based assessment, Bayesian student modelling, and LLM Socratic tutoring - are complementary rather than redundant. KST provides rapid initial classification; Bayesian modelling provides ongoing dynamic

tracking; LLM tutors provide qualitative insight into reasoning processes that quantitative tools cannot capture.

3. The instructor's role in an AI-assisted adaptive curriculum is not eliminated but transformed: from content deliverer to pathway monitor, scaffolding provider, and competency arbiter. Faculty development programmes should equip instructors with the skills to interpret AI diagnostic outputs and exercise informed override authority.

Future research should investigate the implementation of this framework in the specific institutional context of Uzbekistan's technical universities, including the development of KST knowledge spaces for priority engineering disciplines (electrical systems, industrial automation, thermal engineering) and the adaptation of LLM tutoring prompts to domain-specific technical reasoning chains.

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