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# Reconstructing the Textbook Paradigm: From Knowledge Silos to an Interdisciplinary Dynamic Ecosystem for Emerging Engineering Education

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**Abstract:**

*The rapid advancement of intelligent technologies is driving a profound transformation in engineering education towards a competency-development paradigm. However, textbook systems, as a core educational carrier, remain plagued by structural issues including knowledge silos, outdated content, and a disconnect from practical applications. Existing reform efforts are often fragmented , lacking a systematic and sustainable solution. To address this gap, this study follows a design science research approach to proposes and constructs a theoretical framework named the "Interdisciplinary Dynamic Textbook System." This framework (1) employs a knowledge graph as its intelligent backbone, (2) reconstructs knowledge organization around problem-based logic, (3) utilizes a dynamic engine to generate personalized learning paths, and (4) establishes an institutionalized collaboration mechanism for the continuous co-evolution of industrial and educational knowledge.A proof-of-concept implementation, based on a case study of "Intelligent Connected Vehicle System Design," demonstrates the system's efficacy in facilitating interdisciplinary integration and maintaining synchronization with industrial advancements.This study not only provides a scalable design solution to the textbook dilemma but also contributes to theory by proposing a fundamental ontological shift in textbooks—from "static knowledge containers" to "dynamic knowledge ecosystems."*

**Keywords:**

*Emerging Engineering Education Textbooks; Knowledge Graph; Interdisciplinary Integration; Dynamic Systems; Personalized Learning*

## 1. Introduction

The new wave of technological revolution and industrial transformation is driving a fundamental shift in engineering education paradigms, shifting from "adapting to the present" towards "leading the future." Within this context, intelligent technology is regarded as the core enabler empowering this transformation (Li Peigen, 2023). There is an international consensus on the necessity to address complex challenges through interdisciplinary integration and curriculum restructuring, as clearly evidenced by major international policy reports

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such as UNESCO's AI Competency Framework (UNESCO, 2024) and the OECD report What Should Teachers Teach and Students Learn in the Age of AI? (OECD, 2025). This trend is also deeply reflected in China's national strategies. The State Council's Opinions on Deepening the "AI Plus" Initiative (State Council, 2025) explicitly calls for promoting the deep integration of AI throughout the entire educational process, accelerating the fundamental transformation of the educational paradigm from knowledge transmission to competency cultivation.

The textbook system, as a core pedagogical vehicle, is undoubtedly a key lever and critical battleground for achieving the aforementioned paradigm shift. However, the underlying philosophy of traditional textbooks is rooted in a discipline-centered, indoctrination-based educational philosophy, which creates a structural and fundamental contradiction with the "student-centered" and "competency-building" emphasis of emerging engineering education. Specifically, this contradiction manifests in three key dilemmas: (1)in the knowledge dimension, content is organized in isolated and fragmented ways, forming "knowledge silos" that hinder interdisciplinary innovation; (2)in the timeliness dimension, protracted publication cycles lead to outdated content, thus failing to keep pace with rapidly evolving technological frontiers; (3)in the practical dimension, a significant disconnect exists between theoretical instruction and authentic engineering contexts, leaving students facing a significant gap between knowledge comprehension and its transfer and application (Yang Qingnian, 2025; Yang Wenjuan, 2025). These dilemmas collectively reflect a systemic misalignment between the standardized pedagogical supply of the industrial age and the dynamic, personalized talent demands of the digital age (Wang Kaifeng et al., 2025).

In response to these challenges, both academia and industry have initiated active explorations, such as project-based and case-based new-format textbooks. Nevertheless, most of these valuable endeavors remain at the level of incremental improvements: they are either predominantly confined to single courses, failing to achieve interdisciplinary integration; or they focus on the superficial application of technologies like AR/VR, without addressing the core issue of knowledge organization. More critically, significant shortcomings persist in the depth of industry-education integration and the sustainability of dynamic updating mechanisms (Wang Zhen, 2025; Mao Fang, 2025). These fragmented solutions struggle to address the aforementioned triple dilemmas at a fundamental and systematic level. Consequently, a central gap in the current research landscape is the lack of an overarching systematic framework and implementation pathway that can organically integrate interdisciplinary consolidation, dynamic updating, and industry-education collaboration.

Given this context, this study contends that a profound paradigm shift in the textbook system is imperative—transitioning from a static knowledge repository to a dynamic, evolving knowledge ecosystem. To fill the aforementioned core gap, this paper, adhering to the design science research paradigm, proposes an overarching framework termed the "Interdisciplinary Dynamic Textbook System." This framework replaces "disciplinary logic" with "problem logic" as the core engine for knowledge organization, utilizes knowledge graphs as the interconnected intelligent backbone, and deeply integrates institutionalized industry-education collaboration mechanisms with a data-driven, dynamic evaluation and feedback loop.

The contributions of this study are twofold: Theoretically, it transcends the model of partial revisions by providing a systematic theoretical model of a "dynamic textbook ecosystem." Practically, through a proof-of-concept implementation based on a case study, it offers a clear technical pathway and an institutional proto-

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type for resolving the three major structural dilemmas of emerging engineering textbooks.

## 2. Related Work

The paradigm shift towards Emerging Engineering Education ($E^3$) places fundamentally new demands on textbook systems. This section systematically reviews the inherent limitations of traditional textbooks, the shortcomings of current reform initiatives, the technological potential of knowledge graphs, and relevant international practical experiences, with the aim of precisely delineating the starting point and theoretical contribution of this research.

### *2.1 Structural Limitations of Traditional Engineering Textbooks*

The structural limitations of traditional engineering textbooks can trace their theoretical origins to the educational philosophies of behaviorism and cognitivism. This paradigm regards knowledge as a standardized object that can be precisely packaged, efficiently transmitted, and stored in the learner's memory. It has consequently engendered and solidified an indoctrination-based educational model centered on disciplinary knowledge logic and teacher authority, wherein textbooks are assigned the predetermined role of an "authoritative knowledge repository." This creates a fundamental, paradigmatic tension with the student-centered, competency-based paradigms advocated by emerging engineering education, such as constructivism and situated learning. These limitations manifest across three dimensions:

Theoretical Framework Lag: Textbook design rigidly adheres to the systematicity and logical coherence of disciplinary knowledge, resulting in knowledge silos that struggle to integrate emerging interdisciplinary fields, thereby failing to complete the critical transition from "knowledge authority" to "competency scaffold" (Huang Baozhong, 2018; Liu Chao, 2023).

Lack of Practical Context: The linear thinking of "theory first, application later" reduces engineering practice to standardized exercises that merely verify theoretical principles. This approach fails to simulate the complexity, uncertainty, and collaborative nature of modern engineering, consequently creating a significant chasm between "knowledge comprehension" and "knowledge transfer and application," ultimately forming an empowerment gap (Gu Peihua, 2018; Zhao Bingxun, 2023).

Homogeneous Assessment Mechanisms: The evaluation system relies predominantly on passive knowledge checks, such as post-lesson exercises and examinations. It lacks dynamic monitoring of the learning process and personalized support, thus proving ineffective in assessing and fostering students' core competencies like innovative capability and teamwork (Huang Baozhong, 2018; Sun Yan, 2022).

### *2.2 Paradigmatic Limitations of Current Reform Initiatives*

In response to the aforementioned challenges, the academic community has actively explored reforms in pedagogical models, technology application, and institutional mechanisms. However, most of these initiatives have failed to challenge the core paradigm of textbooks as static knowledge repositories, resulting in merely incremental improvements. Their limitations stem from an incomplete transformation of the underlying logic of knowledge organization.

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**(1) Model Exploration: Rigid Problem Logic**

While project-based and case-based textbooks have shifted from disciplinary logic towards problem logic, their content becomes rigidly fixed upon publication. This results in materials that remain essentially pre-packaged, static products, incapable of adapting to technological iterations or learner diversity. They merely replace linear disciplinary knowledge packages with linear project-based knowledge packages (Wang Zhen, 2025; Jiang Chengcheng, 2024).

**(2) Technology Application: Superficial Digitization**

Innovations in digital textbooks have largely focused on the presentation and interaction layers, while their internal knowledge organization often remains a digital replica of the traditional linear structure. This represents a superficial formal innovation that solidifies the outdated core. In this context, technology acts merely as an enhanced medium rather than a driving force for restructuring knowledge architecture, thereby failing to eradicate "knowledge silos" (Mao Fang, 2025).

**(3) Mechanism Innovation: Superficial Industry-Education Integration**

Collaborative textbook development between industry and academia often devolves into sporadic, project-based participation, lacking institutionalized processes and sustainable benefit-sharing mechanisms. Consequently, textbooks quickly fall into a "secondary lag" dilemma post-publication, failing to achieve synchronized evolution with the cutting edge of industrial technology.

In summary, the fundamental limitation of current reform efforts lies in their fragmented nature. They may improve models, apply technologies, or adjust mechanisms in isolation, but they fail to undertake an integrated reconstruction of the textbook's knowledge paradigm, technological backbone, collaborative mechanisms, and evaluation system from a systems engineering perspective. Consequently, they are unable to resolve the systemic challenges facing emerging engineering textbooks, highlighting the urgent need for a top-level systemic design framework.

## *2.3 Research Progress and Frontiers in Educational Knowledge Graphs*

Leveraging their powerful capabilities in semantic association and logical reasoning, knowledge graph technology offers a critical pathway for reshaping the paradigm of educational knowledge organization. Its application is evolving from macro-level curriculum mapping towards micro-level knowledge components that support fine-grained instruction (Canal-Esteve & Gutiérrez, 2024). Existing research amply reveals its significant potential, as evidenced by cutting-edge international explorations, such as constructing interdisciplinary knowledge networks and integrating knowledge graphs with learning analytics to achieve deep personalization. In contrast, current domestic practices focus more on knowledge structuring and resource interconnection within single courses (Xue et al., 2021). A closer examination identifies three core bottlenecks confronting these initiatives: ① Insufficient construction granularity, with most educational graphs remaining at the course level rather than descending to independently recombinable, dynamically deployable "knowledge components." ② Superficial embedding of pedagogical logic, lacking explicit representation of dynamic strategies such as problem-solving logic and instructional design intent. ③ Absence of industry-education update mechanisms, preventing the automatic and efficient transformation of cutting-edge industrial practices

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into teaching resources.

The dynamic textbook system proposed subsequently in this study constitutes a systematic response to the aforementioned research gaps.

## *2.4 A Comparative Study of Interdisciplinary Textbook Systems from an International Perspective*

The application bottlenecks of knowledge graphs discussed earlier fundamentally reflect the systemic challenges in constructing a new generation of textbook systems. To address these challenges, global explorations offer diverse insights; however, their innovations often remain isolated, each touching upon core issues like modularity and collaborative updating from different angles, as summarized in Table 1.

### *2.4.1 European and American Models: Insights and Limitations in Architecture and Ecology*

Germany's modular paradigm transplants industrial standards (e.g., RAMI 4.0) into the educational domain. Its core lies in deconstructing knowledge into standardized, interoperable knowledge components, embodying a strongly engineering-oriented and computable mindset. The U.S. open resource ecosystem (exemplified by MIT OCW) has established a large-scale "contribution-distribution-use" open ecology, achieving a paradigm shift from static products to dynamic services . However, both models primarily emphasize either technical architecture or resource ecology, showing deficiencies in the design of pedagogical logic and the construction of deep collaborative networks.

### *2.4.2 International Organization Frameworks: Value and Gaps in Assessment and Guidance*

International organizations like UNESCO and OECD are committed to guiding textbook development at a global level. UNESCO's (2024) Agile Textbook Assessment Framework emphasizes equity and competency dimensions in textbooks, while OECD (2025) promotes data-driven governance of textbook content through quantitative tools like the Knowledge Currency Index. Their frameworks provide important assessment standards but lack specific guidance on how to internally construct and operate the textbook systems themselves.

### *2.4.3 Asian Practices: Innovation and Dependency in Collaboration and Services*

The National University of Singapore's Tripartite Collaboration Network leverages structured interfaces to systematically translate industry challenges, faculty insights, and student feedback into drivers for textbook iteration. Meanwhile, the Tokyo Institute of Technology's "Textbook-as-a-Service" model deconstructs textbooks into a programmable platform based on microservice components, enabling highly customized instruction. While these practices excel in building collaborative networks and promoting servitization, their effectiveness is often contingent upon specific institutional and cultural settings, and they offer limited innovation to the core logic of knowledge organization.

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*Table 1. A Comparative Analysis of Interdisciplinary Textbook Systems from an International Perspective*

| Country / Organization | Modularization Standard | Update Mechanism | Collaborative Actors | Core Features and Limitations |
|---|---|---|---|---|
| Germany | RAMI 4.0 / VDI 2206 Standards | Synchronized update with industrial standards | Universities + Industry | Features:High degree of engineering orientation and computability;strong industry alignment. Limitations:Insufficient instructional logic design. |
| USA (MIT) | OpenCourseWare Metadata Standards | Continuous integration mechanism of the open ecosystem | Academia + Industry Experts | Features: Open ecosystem and dynamic services; strong resource aggregation capability. Limitations: Weak deep collaboration mechanisms. |
| UNESCO | Agile Textbook Assessment Framework | Multi-dimensional indicator monitoring | International Organizations + Member States | Features: Macro-level assessment and value guidance. Limitations: Lacks specific guidance on system construction and operation. |
| OECD | Knowledge Currency Index | Textbook Health Dashboard | Government + Research Institutions | Features: Data-driven and quantitative governance; focuses on content timeliness. Limitations: Disconnected from the actual teaching context. |
| National University of Singapore | Tripartite Collaboration Interface Standards | Closed-loop feedback mechanism of tripartite collaboration | Enterprises + Universities + Students | Features: Collaborative network with user participation. Limitations: High dependency on specific institutions; limited innovation in the knowledge core. |
| Tokyo Institute of Technology | Micro-service Componentized Architecture | API-driven real-time optimization | Universities + Technology Platforms | Features: Service-oriented platform, agile and programmable; advanced technical pathway. Limitations: Insufficient depth of industry-education integration. |

## *2.5 Literature Summary and Research Gap*

In summary, this review of technological potential and international practices reveals a fundamental contradiction between the systemic complexity of Emerging Engineering Education and the fragmented nature of existing solutions. Knowledge graph technology has yet to evolve into a paradigm-driving intelligent backbone, and while the key success factors from global practices are identifiable, they remain in a state of isolated innovation. Consequently, the most critical gap in current research is the lack of a unified theoretical model and design framework that can deeply couple the systemic perspective of Activity Theory, the network thinking of Connectivism, and key elements from international practices such as modularity, open ecosystems, and collaborative networks. The "Full-Cycle Dynamic Textbook System" proposed in this study constitutes a direct response to this gap. Its objective is not merely to integrate technology and practice, but to provide a systematic engineering blueprint for the new paradigm of "Textbook-as-an-Ecosystem."

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# 3. Materials and Methods

## *3.1 Framework Construction of the Interdisciplinary Dynamic Textbook System*

This section elaborates on the theoretical framework of the "Interdisciplinary Dynamic Textbook System," as depicted in Figure 1. Its core contribution lies in providing an operable and logically self-consistent top-level design model, which aims to systematically resolve the three major dilemmas outlined in the introduction through paradigm reconstruction, technological empowerment, and mechanism innovation.

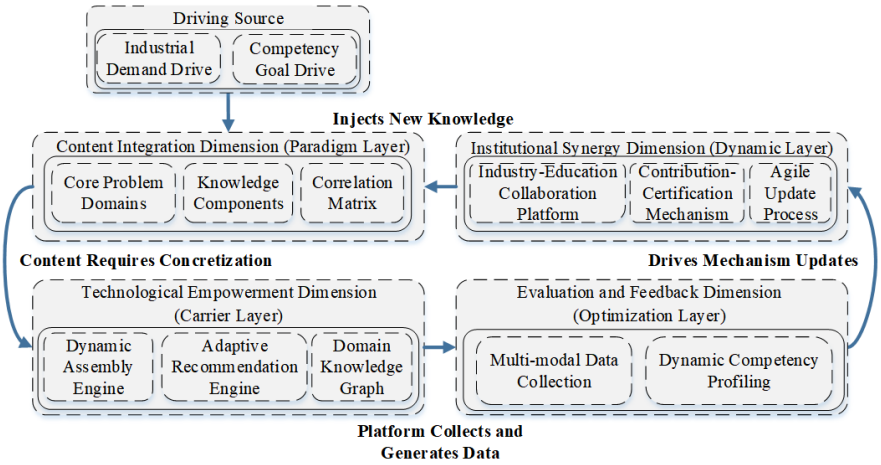



*Figure 1. The Four-Dimensional Theoretical Framework of the Interdisciplinary Dynamic Textbook System*

### *3.1.1 Core Paradigm: Problem-Oriented Knowledge Reconstruction Model*

The core of this system is the replacement of disciplinary chapters with "Core Problem Domains," realizing a paradigm shift from disciplinary logic to problem logic, thereby deconstructing knowledge silos at their source. We constructed a three-layer model called the "Core Problem Domain – Knowledge Component – Correlation Matrix." The structure is as follows:

Driver Layer: Core Problem Domains. Their design adheres to the principles of complexity, openness, and situatedness, constructing a meaningful "Situational Field" derived from Situated Learning Theory (Lave & Wenger, 1991).

Resource Layer: Atomized Knowledge Component Repository. Content is deconstructed into minimal, identifiable units such as concepts, principles, skills, and cases, equipped with standardized metadata to achieve knowledge computability and flexible recombination.

Logic Layer: Interdisciplinary Correlation Matrix. By defining formal semantic relationships, a machine-understandable knowledge graph is constructed, serving as the "Intelligent Skeleton" for achieving knowledge interconnection (Wang et al., 2025).

### *3.1.2 Technological Empowerment: Graph-Driven Dynamic Generation Mechanism*

The technological dimension of the framework aims to translate the paradigm into operational intelligent

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services. We have designed a technical architecture centered around three core engines (Figure 2). It must be emphasized that this framework is a theoretical model, and the following pathways are intended to demonstrate its engineering feasibility.

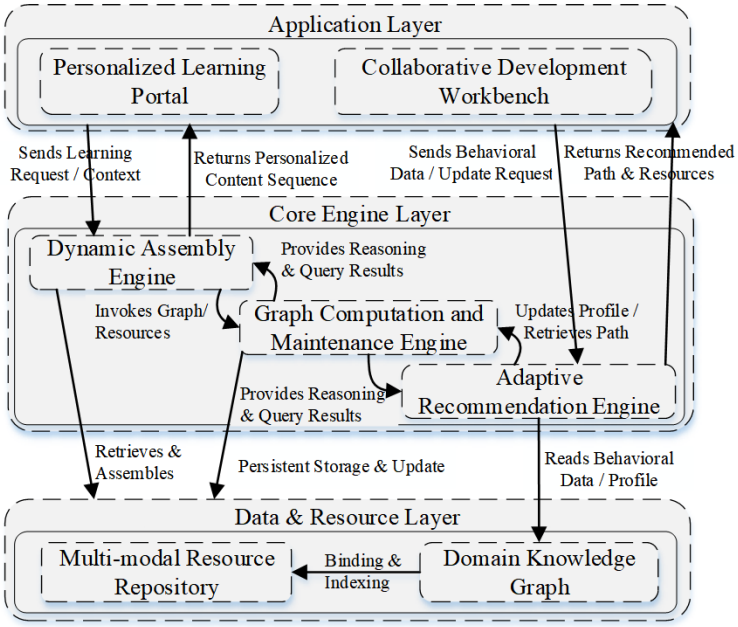



*Figure 2. Core Architecture of the Technological Empowerment Dimension*

Dynamic Assembly Engine: Serving as the "Content Generator," this engine leverages context-aware graph traversal algorithms (Appendix A.1) to generate personalized content sequences in real-time. This algorithm dynamically balances knowledge dependencies, learner profiles, and instructional strategies to output an optimal learning path.

Adaptive Recommendation Engine: Functioning as the "Learning Navigator," this engine relies on a graph neural network-enhanced Deep Knowledge Tracing model (Appendix A.2) to dynamically model the learner's knowledge state. Upon diagnosing knowledge gaps, it can recommend remedial resources or adjust the learning path in real-time.

Domain Knowledge Graph: Acting as the foundational base for the engines, it adheres to W3C standards (RDF, SPARQL), supporting complex semantic queries and logical reasoning.

### *3.1.3 Institutional Synergy: System Design for Ensuring Sustainability*

The sustainability of the framework relies on institutionalizing industry-education collaboration from sporadic cooperation into a knowledge-symbiosis ecosystem. This is achieved through three key mechanisms:

Platform-based Collaboration: Provides structured contribution interfaces that guide industry experts to input standardized cases and pain points, which are then associated with nodes in the knowledge graph. This ensures machine readability and industry relevance of the content from its source.

Contribution-Certification Mechanism: Designs a model for quantifying contribution levels (based on volume, quality, and impact) and links them to faculty performance evaluation and corporate social responsibili-

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ty certification, thereby creating a sustainable internal driving force.

Agile Update Process: Drawing on the DevOps philosophy from software engineering, it establishes a closed loop of "continuous integration – gradual rollout – A/B testing." This allows approved content to be deployed immediately and drives its continuous optimization through learning feedback data, fundamentally solving the problem of update lag.

### *3.1.4 Evaluation and Feedback: Data-Driven Process Empowerment*

This dimension aims to construct an intelligent closed loop of "Assessment-Diagnosis-Intervention-Optimization," transforming evaluation from static measurement into dynamic process empowerment and system optimization. Its operation relies on a four-stage model:

Multi-modal Data Collection and Fusion: Automatically collects and integrates multi-dimensional student data, including cognitive behaviors, procedural operations, and final artifacts, to construct a Learning Journey Graph.

Dynamic Competency Profiling and Diagnosis: Leverages models such as Item Response Theory to map behavioral data into dynamically updated individual and group competency profiles, enabling precise diagnosis of knowledge gaps and content deficiencies (Vie & Kashima, 2023).

Personalized Feedback and Intervention: Provides real-time feedback and path adjustments based on the competency profiles, deeply embedding formative assessment into the learning process.

System Optimization Decision Support: Evaluation data feeds back to drive the self-evolution of the textbook system. Common learning difficulties automatically trigger content optimization tasks, thereby transforming textbooks into an intelligent, perceptive system capable of analysis, decision-making, and action.

## *3.2 Validation Method: Case Design and Feasibility Demonstration*

To validate the feasibility of the proposed framework, this study adheres to the design science research paradigm and adopts a case study method of "simulation via a design prototype." This approach aims to provide a proof-of-concept for the core mechanisms, demonstrating their logical self-consistency and implementation feasibility (Carstensen & Bernhard, 2019). Using "Intelligent Connected Vehicle (ICV) System Design" as the core problem domain, we constructed a design prototype and conducted simulations through the following steps:

(1)Micro-level Knowledge Graph Construction: A micro-level knowledge graph for the chosen domain was manually constructed, defining core knowledge components and their interrelationships to simulate the foundational domain knowledge graph.

(2)Path Generation Simulation: The logic of the dynamic assembly engine was detailed, demonstrating how it generates differentiated learning paths for different learners based on the knowledge graph, thereby simulating its personalized generation capability.

(3)Collaborative Process Demonstration: The entire workflow, from the contribution of a new industry

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technology case, through its instructional design, to its final integration into the knowledge graph, was simulated to verify the feasibility of the update mechanism.

Through this case simulation, the study provides a solid proof-of-concept for the framework, laying a foundation for subsequent development and empirical research.

# 4. Results

To evaluate the feasibility and potential effectiveness of the proposed framework, we conducted a case simulation and a user study following the validation method described in Section 3.2. The results provide preliminary evidence for the framework on two key fronts: the system's operational mechanics and its perceived user value.

## *4.1 Case Implementation: Micro-level Knowledge Graph Construction and Dynamic Assembly Demonstration*

### *4.1.1 Micro-level Knowledge Graph Construction*

To validate the framework's feasibility, we manually constructed a micro-level knowledge graph for the "Intelligent Connected Vehicle (ICV) System Design" case. This graph defines 28 core knowledge components spanning four disciplines, including Vehicle Engineering and Computer Science (see Appendix Table B1 for the complete list), and employs a set of formalized semantic relationships (see Appendix Table B2 for the complete definitions) to precisely characterize their complex interactions.

As shown in Figure 3, the graph clearly illustrates how core modules, such as environmental perception and decision-making planning, are interconnected through semantic relationships and ultimately integrated under a unified system architecture. This semantically rich structure provides intuitive validation of the system's feasibility in achieving interdisciplinary knowledge integration.

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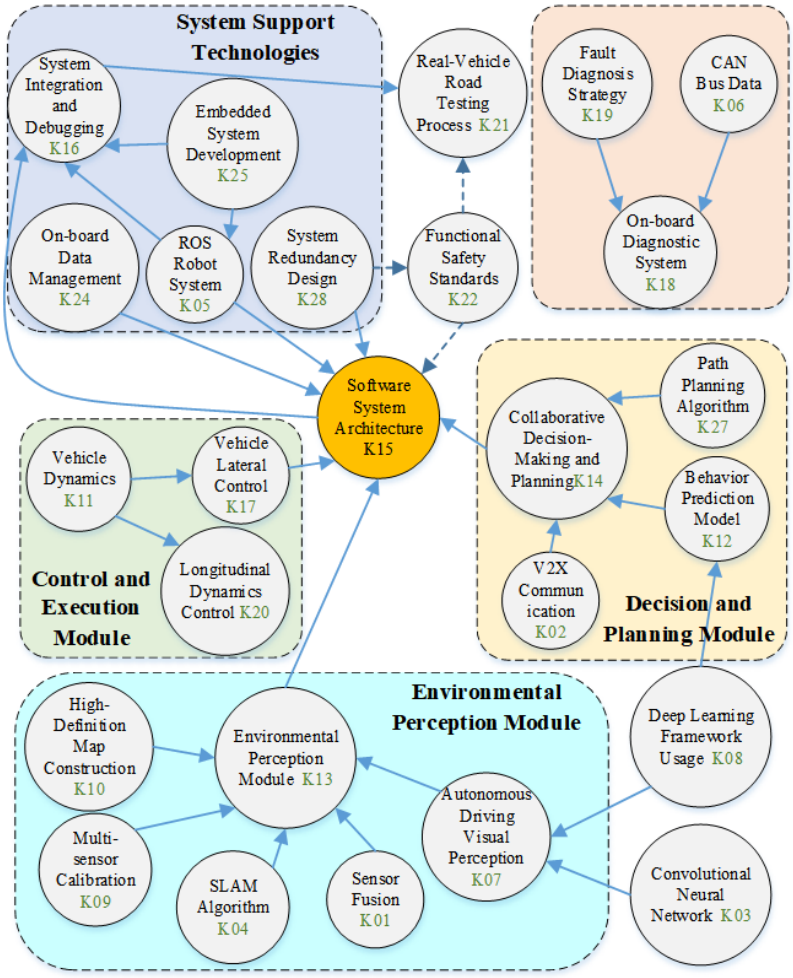



*Figure 3. A Subgraph of Core Relationships in the Knowledge Graph for the "Intelligent Connected Vehicle System Design" Case.*

### *4.1.2 Dynamic Assembly and Path Generation*

To validate the personalized generation capability of the Dynamic Assembly Engine, we simulated two virtual learners with different disciplinary backgrounds (User A, inclined towards software and algorithms; User B, inclined towards mechanics and hardware) based on the aforementioned knowledge graph.

**(1) Simulation of Path Generation Mechanism**

The Dynamic Assembly Engine, taking the Core Problem Domain as the root node, performs an intelligent exploration within the knowledge graph based on a context-aware graph traversal algorithm (Appendix A.1). This algorithm dynamically weighs knowledge dependencies, the learner's initial state, and instructional strategy objectives to generate a logically coherent learning sequence that meets personalized needs.

**(2) Comparative Analysis of Personalized Paths**

The system generated two distinct learning paths (Table 2). Path A ("Perception-Decision Driven System Implementation") started from K07 "Autonomous Driving Visual Perception," focusing on algorithms and

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making interdisciplinary connections leading to system integration. Path B ("Vehicle Platform Integration and Intelligence") initiated from K11 "Vehicle Dynamics," deepening the understanding of hardware while supplementing knowledge of software architecture.

*Table 2. Comparison of Dynamically Assembled Paths for Learners with Different Backgrounds*

| Comparison Dimension | Path A: Software/Algorithm Background Learner | Path B: Mechanical/Hardware Background Learner |
|---|---|---|
| Path Name | "Perception-Decision Driven System Implementation" Path | "Vehicle Platform Integration and Intelligence" Path |
| Primary Focus | Strengthens algorithm comprehension and application, supplemented with essential knowledge of system integration and vehicle dynamics. | Deepens understanding of the vehicle platform and hardware, supplemented with knowledge of software architecture and AI algorithms. |
| Starting Component | K07 Autonomous Driving Visual Perception | K11 Vehicle Dynamics |
| Core Knowledge Sequence | 1. K07 Autonomous Driving Visual Perception →<br>2. K03 Convolutional Neural Network / K08 Deep Learning Framework Usage →<br>3. K12 Behavior Prediction Model / K14 Collaborative Decision-Making and Planning →<br>4. **[Interdisciplinary Bridge]** K05 ROS Robot System →<br>5. K15 Software System Architecture / K16 System Integration and Debugging | 1. K11 Vehicle Dynamics →<br>2. K17 Vehicle Lateral Control / K20 Longitudinal Dynamics Control →<br>3. K06 CAN Bus Data / K18 On-board Diagnostic System →<br>4. **[Interdisciplinary Bridge]** K25 Embedded System Development →<br>5. K05 ROS Robot System →<br>6. K15 Software System Architecture / K01 Sensor Fusion |
| Representative Practical Activity | Develop a simple vehicle perception module based on ROS and a deep learning framework in a virtual lab. | Perform CAN bus data acquisition and analysis in a simulation environment, and integrate an embedded node that executes control commands. |

**(3) Discussion of Path Generation Results**

The simulation results fully demonstrate the effectiveness of the Dynamic Assembly Engine:

Achieving True Personalization: Path A starts with an algorithmic case, while Path B begins with vehicle principles. The engine tailors the learning journey for learners starting from different points.

Ensuring Interdisciplinary Integrity: Both paths ultimately converge on the core objective of K15 "Software System Architecture," ensuring all learners develop the systemic perspective required to solve complex engineering problems.

Deconstructing "Knowledge Silos": Knowledge is organically integrated during the process of solving the core problem. For instance, for the software-background learner, K05 "ROS Robot System" is no longer an isolated computer science topic but becomes the necessary carrier and tool for implementing their algorithms (K07, K14).

### *4.1.3 Demonstration of the Industry-Education Collaboration Process*

To validate the industry-education collaboration mechanism, we simulated the complete process of integrating the cutting-edge industrial technology "Deep Learning-based LiDAR Point Cloud Recognition for

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Vehicles" into the "Intelligent Connected Vehicle System Design" knowledge graph. This simulation fully demonstrates the institutionalized collaborative workflow.

**(1) Industrial Contribution: Structured Input**

A scenario was simulated where an engineer from an autonomous driving company submits a case through the platform's structured contribution interface, as shown in Table 3. Using a guided form, the contributor standardizes inputs for technical pain points, solutions, and key metrics, ensuring the machine readability and pedagogical relevance of the industrial knowledge from the source.

*Table 3. Example of a Structured Industrial Case Contribution*

| Field Category | Field Name | Example Input (Using "Vehicle LiDAR Point Cloud Recognition Technology" as a case) |
|---|---|---|
| Case Description | Technical Pain Point Description | Traditional recognition methods suffer from low point cloud signal-to-noise ratio in adverse weather conditions, leading to a significant drop in detection accuracy. |
| | Core Solution Description | An improved PointNet++ model based on an attention mechanism is employed to effectively focus on valid point clouds and suppress noise interference. |
| Technical Parameters | Key Performance Indicator(s) | The mean Average Precision (mAP) is increased to 85%. |
| | Reference Data / Resources | A standardized training subset containing 1000 frames of point cloud data with annotations for various scenarios including clear weather, rain, and fog. |
| Pedagogical Association | Associated Knowledge Components | K01 Sensor Fusion, K03 Convolutional Neural Network, K07 Autonomous Driving Visual Perception |
| | Suggested Learning Context | Serves as an advanced case analysis for the "Environmental Perception Module". |

Note: The content in the table is a simulated input example for demonstrating the structured contribution process.

**(2) Pedagogical Design: From Case to Component**

After submission, the platform's workflow engine automatically triggers a task, assigning this industrial case to a university teacher responsible for the "Environmental Perception" domain. The teacher team follows a standardized process to transform it into a "Teaching Case Component" ready for integration into the knowledge graph. The specific design process is as follows:

Theoretical Elevation and Association: The industrial solution is associated with existing theoretical components in the knowledge graph, thereby deepening the theoretical content. For instance, associating the "Improved PointNet++ Model" with the K03 ("Convolutional Neural Network") component anchors the industrial technology in theory while simultaneously expanding the knowledge boundaries of the original theoretical component.

Situated Instructional Design: Operable teaching activities are designed around the industrial case to facilitate the transformation of knowledge into competency. For example, designing a practical task such as "Adjust the model's attention weights and analyze its impact on the recognition rate of point clouds affected by rain and fog noise," allowing students to intuitively understand the algorithm's principles through experi-

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mentation.

Multi-modal Resource Binding: Necessary learning resources are systematically associated to support the implementation of teaching tasks. Examples include linking the original research paper, basic code templates, and instructional micro-videos demonstrating key operations.

Standardized Packaging and Review: All the above elements are packaged into a unified "Teaching Case Component" according to a standardized metadata template, which then enters a cross-review process to ensure its accuracy, pedagogical soundness, and correct association with the knowledge graph.

**(3) Agile Integration and Push Phase: Realizing the Closed Loop and Value Verification**

Once approved, the new component is instantly released into the knowledge graph via a CI/CD pipeline, establishing semantic links with related components.

① Immediate Activation and Continuous Integration: After approval, the new component is automatically integrated and deployed via the CI/CD (Continuous Integration/Continuous Deployment) pipeline, becoming part of the knowledge graph. This reduces content update latency to "minutes," achieving near-synchronization with technological advancements.

② Data-Driven Precision Pushing: The system executes an intelligent gradual rollout strategy based on real-time analysis of learner profiles and behavioral data. For instance, it immediately notifies learners currently studying the "Environmental Perception Module" (K13) and recommends it to users with potential interest, such as those who recently searched for keywords like "point cloud" or "LiDAR," shifting the paradigm from "learners seeking knowledge" to "knowledge finding learners."

③ Feedback-Driven Evolution Loop: After publication, the system automatically initiates a quality lifecycle management for the new component. When negative feedback or low completion rates accumulate to a predefined threshold, the system automatically generates a "Content Optimization Ticket" and triggers a revision process, thereby forming a continuous evolution loop of "release → feedback → optimize → re-release."

Through this simulation, the study verifies the dual advantages of this mechanism in terms of operational feasibility and problem-solving efficacy: it systematically addresses the issue of content update lag and, through institutionalized interfaces and data-driven strategies, significantly mitigates the disconnection between theory and practice.

## *4.2 User Acceptance and Perceived Effectiveness Analysis*

To evaluate the feasibility and potential value of the proposed system in practical application scenarios, we conducted a systematic user study aimed at investigating the acceptance of target users (students and teachers) and their perceived core advantages.

### *4.2.1 Evaluation Methods and Tools*

This study involved 80 students and 10 teachers from an emerging engineering education experimental program at a university, who participated in the experience and evaluation. A mixed-methods approach was

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adopted:

Quantitative Questionnaire: A 20-item questionnaire using a five-point Likert scale was designed, covering four dimensions: Perceived Usefulness, Perceived Ease of Use, Perceived Interdisciplinary Integration, and Behavioral Intention to Use. The questionnaire demonstrated good reliability, with a Cronbach's α of 0.91.

Qualitative Interviews: Based on the questionnaire results, 12 participants (8 students, 4 teachers) were purposively sampled for semi-structured interviews to gain deeper insights into the reasons behind their experiences.

### *4.2.2 User Acceptance Results*

Questionnaire results indicated that the system received positive evaluations from users across all core dimensions (Overall Mean = 4.29/5.00). Detailed data is presented in Table 4. Among these, Perceived Usefulness (Mean=4.37) and Perceived Interdisciplinary Integration (Mean=4.44) scored the highest, indicating strong user recognition regarding "understanding knowledge application in context" and "content alignment with the industrial frontier." The Perceived Ease of Use score was relatively lower, with some users providing feedback that the knowledge graph interface had a learning curve.

*Table 4. User Acceptance Questionnaire Results by Dimension (Mean ± Standard Deviation)*

| Evaluation Dimension | Students (*n*=80) | Teachers (*n*=10) | Overall (*N*=90) |
|---|---|---|---|
| Perceived Usefulness | 4.35 ± 0.52 | 4.50 ± 0.41 | 4.37 ± 0.51 |
| Perceived Ease of Use | 4.18 ± 0.61 | 4.20 ± 0.55 | 4.18 ± 0.60 |
| Perceived Interdisciplinary Integration | 4.42 ± 0.48 | 4.55 ± 0.39 | 4.44 ± 0.47 |
| Behavioral Intention to Use | 4.15 ± 0.65 | 4.40 ± 0.52 | 4.18 ± 0.64 |
| Overall Rating | 4.28 ± 0.49 | 4.41 ± 0.42 | 4.29 ± 0.48 |

### *4.2.3 Qualitative Findings*

Thematic analysis of the interview data further revealed the valued aspects and potential areas for improvement.

① Positive Experiences:

Context-Driven Knowledge Integration: Over 90% of the interviewed students mentioned that the "Core Problem Domains" provided them with an unprecedented clarity regarding the application scenarios of knowledge.

Effectiveness of Personalized Paths: Students highly appreciated the personalized paths generated by dynamic assembly, noting that they effectively addressed the pedagogical conflict of "some content being too basic or too difficult to follow."

Timeliness of Industry Cases: Teachers particularly valued the industry-education collaboration mecha-

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nism, believing it ensures the teaching case library stays synchronized with the technological frontier.

② Suggestions for Improvement:

Interface Interaction Optimization: Some users suggested providing simpler navigation and guidance for the knowledge graph view.

Collaboration Feature Enhancement: Teachers expressed a desire for the platform to integrate more robust collaborative editing and version comparison features to support more in-depth interdisciplinary course development.

Through the in-depth simulation of the "Intelligent Connected Vehicle System Design" case and the systematic user study, this chapter provides solid preliminary evidence for the proposed Interdisciplinary Dynamic Textbook System from two dimensions: system operational mechanics and user perceived value. The results demonstrate that the system possesses significant feasibility and application potential in achieving interdisciplinary knowledge integration, ensuring content timeliness, and providing personalized learning experiences.

# 5. Discussion

This chapter aims to provide an in-depth interpretation and comprehensive synthesis of the findings from Chapter 4. It situates the specific empirical evidence within the broader context of Emerging Engineering Education, textbook research, and educational technology development, systematically elaborating on the theoretical contributions and practical implications of this study, candidly reflecting on its limitations, and pointing out directions for future research.

## *5.1 Theoretical Contributions: Reconstructing and Expanding the Paradigm for E³ Textbooks*

This study moves beyond fragmented improvements to traditional textbooks, systematically conceptualizing and providing preliminary validation for a new paradigm of the "Dynamic Textbook Ecosystem," thereby repositioning the textbook as the core knowledge infrastructure for Emerging Engineering Education.

### *5.1.1 From "Knowledge Repository" to "Knowledge Ecosystem": The Evolution of Textbook Ontology*

The high score for "Perceived Interdisciplinary Integration" (4.44/5.0) in the user study strongly supports the validity of defining the textbook as a "dynamic knowledge ecosystem." This marks a fundamental shift in the theoretical positioning of textbooks from static knowledge carriers towards dynamic cognitive scaffolds and competency-generating fields. The framework technologizes and structures the "community of practice" concept from Situated Learning theory, transforming "learning in context" from a pedagogical principle into a scalable core of the textbook (Giles & Pitonyak, 2025).

### *5.1.2 "Problem Logic" as a Systematic Engine for Interdisciplinary Integration*

The successful generation of two distinct paths in the case study demonstrates that "Core Problem Do-

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mains" are not merely teaching cases but serve as a systematic mechanism driving the organic integration of interdisciplinary knowledge. It respects learners' prior knowledge, constructs personalized yet goal-unified cognitive maps, transcends project-based reforms within single courses, and provides a theoretical and practical tool for knowledge reorganization and delivery at the program or even ecosystem level.

### *5.1.3 Theoretical Dialogue: From Theoretical Explanation to Engineering Blueprint for Paradigm Construction*

The deeper value of the framework lies in its engineering transformation of Activity Theory and Connectivism, converting them from descriptive paradigms into constructible and operable system blueprints.

① The Engineering of Activity Theory: Through the concretization of tools (knowledge graphs, platform) and the codification of rules (contribution-certification mechanism), this framework solidifies Activity Theory from a lens for analyzing dynamic activities into a designable, operable educational infrastructure, providing an engineering pathway for macro-level industry-education integration.

② The Paradigm Upgrade of Connectivism: Through the structuring of the ecology (knowledge graph as the "knowledge garden") and the servitization of connections (dynamic engines as intelligent "connection brokers"), the framework upgrades "connections" from cognitive strategies reliant on the individual to large-scale, system-guided teaching services, significantly enhancing efficiency while preserving exploratory freedom.

By leveraging technological empowerment and mechanism design, this study systematically addresses the lack of constructive guidance in Activity Theory and the limitations in practical efficiency of Connectivism. This cross-theoretical integration model promotes the operational transformation of classical theories.

## *5.2 Comparative Advantages of the Framework: A Systematic Comparison with Traditional and Cutting-edge Textbook Models*

As shown in Table 5, the Dynamic Textbook System constructed in this study achieves paradigmatic superiority over existing textbook models across six core dimensions, including knowledge organization, update mechanisms, and industry-education integration.

*Table 5. A Comparison between the Interdisciplinary Dynamic Textbook System and Existing Textbook Models*

| Comparison Dimension | Traditional Textbooks | Project-based/ Case-based Textbooks | Digital Textbooks (e.g., AR/VR, E-books) | Proposed Dynamic Textbook System |
|---|---|---|---|---|
| Knowledge Organization Logic | Discipline-centered, linear structure | Problem/Project-centered, yet often confined to a single course | Media-rich, but the core is often a digitized version of traditional linear content | Interdisciplinary Problem Domain-driven, interconnected via Knowledge Graph |
| Update Mechanism & Cycle | Version-based updates, long cycle (years) | Version-based updates, long cycle (years) | Version-based updates, cycle somewhat shortened | Continuous integration, agile updates, near real-time |

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| | | | | |
|---|---|---|---|---|
| Industry-Education Integration Depth | Largely disconnected, or mentioned briefly in prefaces/ isolated cases | Cases may originate from industry but become fixed upon publication | May integrate multimedia cases, but updates lag | Institutionalized, full-lifecycle collaboration, forming a knowledge-symbiosis ecosystem |
| Personalization Level | Non-differentiated, uniform path | Limited personalization, reliant on teacher's real-time adjustment | Enables adaptive exercises, but the knowledge organization itself is fixed | Dynamic path generation based on competency profiles & knowledge graphs, highly personalized |
| Technology Empowerment Level | Minimal technological empowerment | Superficial technology application (e.g., online resources) | Focuses on presentation-layer tech (immersion, interactivity) | Driving-layer technologies (Knowledge Graphs, AI algorithms) restructure the knowledge core and processes |
| Evaluation & Feedback Mechanism | Static, summative assessment (e.g., exercises, exams) | Combines process and summative assessment, but difficult to analyze at scale | Can collect some process data, but analysis and feedback are limited | Data-driven, full-process, diagnostic & optimization integrated intelligent closed loop |

Compared to traditional textbooks, the proposed system fundamentally resolves the issues of knowledge silos and update lag. Compared to project-based/case-based textbooks, it achieves content dynamism and cross-course/disciplinary scalability through its technical architecture. Compared to digital textbooks focusing on media format innovation, it reconstructs the very core of knowledge organization and deeply integrates mechanisms for industry-education collaboration and personalization. Consequently, this system represents a fundamental shift from a static knowledge carrier to a dynamic knowledge ecosystem.

### *5.3 Practical Implications*

The framework and findings of this study provide clear direction for reconstructing the textbook system for Emerging Engineering Education, offering direct implications for key stakeholders such as universities, policymakers, and industry. Specific systematic action pathways will be elaborated in the Conclusion section.

### *5.4 Limitations and Future Directions*

We duly acknowledge the limitations of this study, which also point to clear avenues for future research.

First, the simulated nature of the case validation and its limitations in generalizability. This study is based on an in-depth simulation of a typical engineering case; its effectiveness awaits long-term, large-scale empirical testing in real teaching environments. Future work should conduct comparative studies and teaching experiments across disciplines and institutions to evaluate its educational value and ecological adaptability.

Second, the sustainability challenge during the initial system phase. The long-term viability of the framework highly depends on an active industry-education community, which often faces the dilemma of scarce initial content and a weak participation network at the launch stage. Although a contribution-certification mechanism has been designed, its effectiveness at a larger scale still requires empirical verification. Future work could explore innovative incentive schemes, such as decentralized contribution measurement and value

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return based on blockchain technology, to stimulate network effects at a lower cost.

Third, the inherent tension between deep personalization and unified assessment. Personalized learning paths pose a challenge to standardized assessment systems. Future efforts need to concurrently innovate more flexible, competency-based assessment paradigms, for which the comprehensive learning process data generated by this system provides a rich foundation.

Fourth, the need for a more robust technological ethics and governance framework. Future research must prioritize ethical considerations, committing to the construction of a transparent data security and algorithm auditing governance framework embedded within the system itself, ensuring the protection of students' digital rights and right to development while leveraging technological empowerment.

# 6.Conclusion and Outlook

## *6.1 Research Conclusions*

Confronting the core contradiction between emerging engineering textbooks and talent development needs, and following the design science research paradigm, this study has achieved decisive advancements in three key areas:

First, a paradigm-breaking theoretical framework. We have originally constructed a four-dimensional, integrated dynamic textbook ecosystem framework comprising "Problem Logic - Knowledge Graph - Institutional Synergy - Data Closed Loop," establishing a new paradigmatic pathway from a static knowledge repository to a dynamic knowledge ecosystem.

Second, a proof-of-concept for the core mechanisms. Through case simulation and user studies, we have demonstrated the system's unique advantages in generating personalized paths, integrating interdisciplinary knowledge, and seamlessly incorporating industrial technology. Its value in enhancing learning contextualization and content currency has received strong user recognition.

Third, a practical blueprint and template. The system provides an integrated technical pathway and institutional prototype for resolving the three major dilemmas of emerging engineering education. Its core lies in using a paradigm shift to deconstruct knowledge silos, institutional innovation to eradicate update lag, and ecosystem operation to bridge the theory-practice gap.

In summary, this study has completed the full cycle from theoretical construction to conceptual validation for the new paradigm, laying a solid foundation for subsequent empirical research and ecosystem operation.

## *6.2 Practical Implications and Recommendations*

Based on the conceptual validation results of this study, we propose the following action guidelines for key stakeholders within the educational practice community:

For universities and teachers, the key is to adopt an implementation strategy of "starting from specific points and expanding to broader areas, evolving through collaboration." At the institutional level, universities

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must implement supporting reforms to faculty evaluation and incentive systems, recognizing contributions to content development, knowledge graph construction, and industry-education collaboration as core academic labor. At the individual level, teachers should actively engage in curriculum restructuring based on knowledge graphs and interdisciplinary teaching innovation, collectively promoting the continuous evolution of the textbook ecosystem.

For educational administrators and policymakers, the focus should be on top-level design. The development level and application effectiveness of dynamic, open textbook resources should be incorporated as core indicators in engineering education accreditation and teaching assessments, using evaluation to drive construction and guide resource allocation towards the new infrastructure of future education.

For industry enterprises and publishers, we advocate moving beyond traditional cooperation models. Enterprises should view this as a strategic investment in forward-looking talent development and social responsibility. Publishers need to transform into knowledge service operators and ecosystem coordinators that connect education, industry, and technology.

### *6.3 Future Outlook*

The completion of this study lays the groundwork for subsequent exploration. Future research should deepen efforts in the following directions:

Expanding Research Scope and Ecological Adaptability: There is an urgent need for multi-case comparative studies across different regions, cultures, and types of institutions to test the universality of the framework and explore specific models for its adaptation and scaling within diverse educational ecosystems.

Tracking Long-term Effects and Educational Value: Long-term longitudinal studies of users must be initiated. Examining the lasting impact of the system on students' innovation capabilities, lifelong learning competencies, and career trajectory from the perspective of graduate career development is crucial for validating its educational value over a longer term.

Building a Technological Ethics and Governance Framework: With the large-scale collection and application of educational data, future research must prioritize ethical considerations, committing to the construction of an embedded, transparent governance framework for data security and algorithm auditing to ensure the protection of students' digital rights while leveraging technological empowerment.

Exploring Sustainable Operational Models: The core of the system's development lies in constructing a sustainable value closed loop. Future research should explore decentralized operation and contribution measurement systems based on technologies like blockchain to drive industry-education collaboration at low cost and high efficiency, ensuring the autonomous evolution and long-term vitality of the knowledge ecosystem.

In conclusion, the value of this research lies not only in constructing an effective framework but, more profoundly, in revealing the evolutionary direction of the textbook paradigm: it must inevitably transition from static print to flowing intelligence, from a passive knowledge carrier into a living ecosystem that breathes and co-evolves with learners, educators, and industry. Promoting this fundamental transformation is an imperative requirement for cultivating exceptional innovators capable of navigating future complexities.

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# Appendix

## *Appendix A*

This appendix aims to provide more specific technical implementation pathways for the core engines described in Section 3.1.2, to demonstrate their engineering feasibility.

### *A.1 Graph Traversal Algorithm for the Dynamic Assembly Engine*

The core algorithm flow of the Dynamic Assembly Engine is illustrated in Figure A1, whose objective is to identify an optimal path from a starting knowledge component to a set of target components, adhering to instructional constraints.

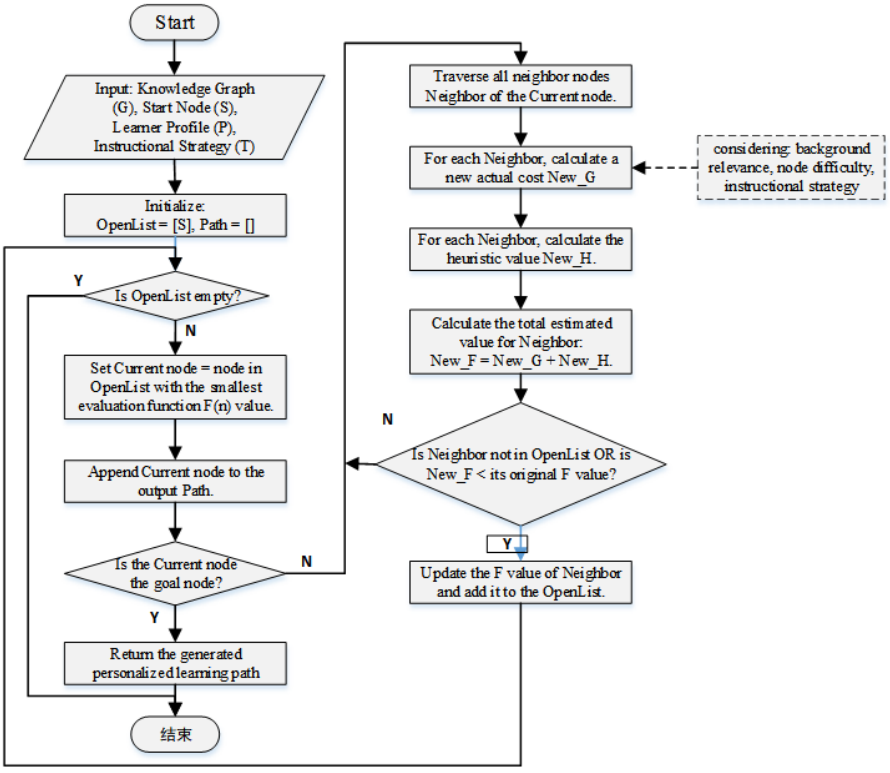



*Figure A1. Flowchart of the Dynamic Assembly Engine Algorithm.*

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**Algorithm 1**: Context-Aware Knowledge Path Generation Algorithm (Pseudocode)

Input: Knowledge Graph G, Start Node S, Goal Node Goal, Learner Profile P, Instructional Strategy T

Output: An ordered sequence of knowledge components Path (a path from S to Goal)

1: Initialize open list OpenList ← [S], Path ← []

2: Initialize scoring function F(n) = G(n) + H(n) // G(n) is the accumulated cost from

//S to node n; H(n) is the heuristic estimated cost from node n to the final Goal

3: WHILE (OpenList is not empty) DO

4: Current node Current ← node in OpenList with the smallest F value

5: Append Current to Path

6: IF (Current == Goal) THEN RETURN Path

7: FOR (each neighbor node Neighbor □ G.adjacentNodes(Current)) DO

8: IF (Neighbor □ Path) THEN CONTINUE // Skip neighbors already in Path to

// prevent cycles

9: New_G = ComputeCost(Neighbor, P, T, Path) // Computes the actual cost from S to

// Neighbor, ensuring path alignment with the learner's background and cognition

10: New_H = HeuristicEstimate(Neighbor, Goal, T) // Calculates the heuristic

// function H, estimating the cost from Neighbor to the Goal node

11: New_F = New_G + New_H

12: IF (Neighbor is not in OpenList OR New_F< existing F value of Neighbor)THEN

13: Update the F value of Neighbor to New_F

14: Set the parent of Neighbor to Current // Used for final path reconstruction

15: IF (Neighbor is not in OpenList) THEN

16: Add Neighbor to OpenList

17: END IF

18: END IF

19: END FOR

20: END WHILE

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21: RETURN Path // Returns the generated learning path

## *A.2 Model Architecture of the Adaptive Recommendation Engine*

The Adaptive Recommendation Engine employs a Graph Neural Network-enhanced Deep Knowledge Tracing (GNN-enhanced DKT) model, whose architecture is depicted in Figure A2. This model integrates students' historical interaction sequences with the structural information of the knowledge graph to jointly predict their future exercise performance.

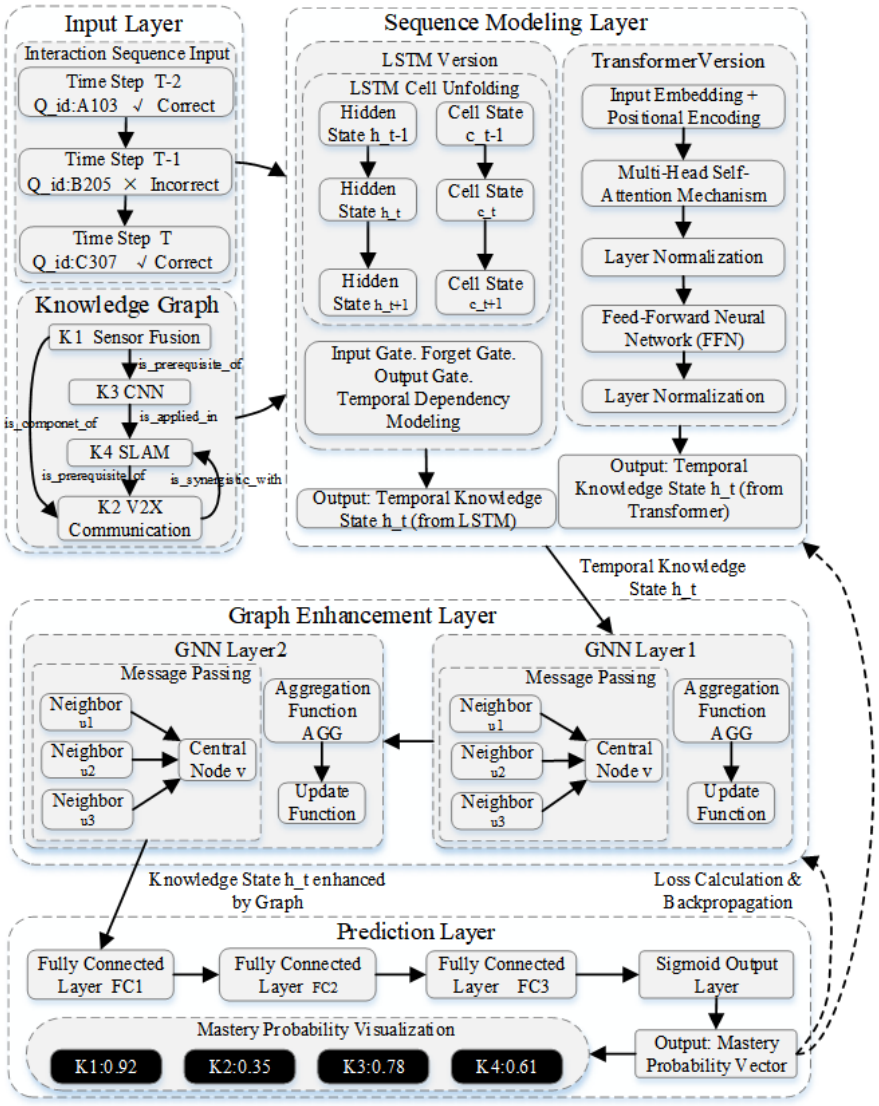



*Figure A2. Architecture of the GNN-enhanced DKT Model.*

Description of the GNN-enhanced DKT Model Architecture:

Input Layer: Receives two types of information. The interaction sequence records the learner's historical exercise records (question IDs and correctness), reflecting their learning process. The knowledge graph defines the semantic relationships between knowledge components, providing a structured context of knowledge.

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Sequence Modeling Layer: Utilizes an LSTM or Transformer model to process the interaction sequence. Its core function is to capture the temporal dependencies within learning behaviors, outputting a vector representation that comprehensively reflects the learner's recent knowledge state.

Graph Enhancement Layer: Employs the message-passing mechanism of a Graph Neural Network to diffuse and enhance the knowledge state (output from the Sequence Modeling Layer) across the structure of the knowledge graph. This allows the states of related knowledge components to influence each other, thereby generating a richer knowledge state representation that incorporates knowledge relationships.

Prediction Layer: Takes the enhanced knowledge state as input, applies non-linear transformation via a fully connected neural network, and finally outputs the mastery probability for each knowledge component through a Sigmoid function. This probability vector can be directly used for personalized learning path recommendations and resource allocation.

## Appendix B:

*Table B1. Knowledge Components and Relationships in the "Intelligent Connected Vehicle System Design" Micro Knowledge Graph*

| Component ID | Knowledge Component Name | Disciplinary Affiliation | Component Type | Core Semantic Relationships |
|---|---|---|---|---|
| K01 | Sensor Fusion | Artificial Intelligence / Electronics | Conceptual | is_prerequisite_of K09; is_component_of K13 |
| K02 | V2X Communication | Electronics / Computer Science | Conceptual | is_synergistic_ with K09; is_applied_ in K14 |
| K03 | Convolutional Neural Network | Artificial Intelligence | Principle/ Method | is_applied_in K07; is_ prerequisite_of K08 |
| K04 | SLAM Algorithm | Artificial Intelligence / Computer Science | Principle/ Method | is_prerequisite_ of K10; is_applied_in K13 |
| K05 | ROS Robot System | Computer Science | Skill/Process | is_component_of K15; is_ prerequisite_of K16 |
| K06 | CAN Bus Data | Vehicle Engineering / Electronics | Skill/Process | is_applied_in K18; is_ prerequisite_of K19 |
| K07 | Autonomous Driving Visual Perception | Artificial Intelligence | Case/ Situational | is_component_ of K13; utilizes K03 |
| K08 | Deep Learning Framework Usage | Computer Science / Artificial Intelligence | Skill/Process | is_applied_in K07, K12 |
| K09 | Multi-sensor Calibration | Electronics / Vehicle Engineering | Skill/Process | is_prerequisite_of K13 |
| K10 | High-Definition Map Construction | Computer Science / Artificial Intelligence | Case/ Situational | is_component_ of K13; utilizes K04 |
| K11 | Vehicle Dynamics | Vehicle Engineering | Principle/ Method | is_prerequisite_of K17, K20 |
| K12 | Behavior Prediction Model | Artificial Intelligence | Principle/ Method | is_applied_ in K14; utilizes K08 |

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| | | | | |
|---|---|---|---|---|
| K13 | Environmental Perception Module | Artificial Intelligence / Electronics | Case/ Situational | is_component_ of K15; integrates K01, K04, K07 |
| K14 | Collaborative Decision-Making and Planning | Artificial Intelligence / Computer Science | Case/ Situational | is_component_ of K15; utilizes K02, K12 |
| K15 | Software System Architecture | Computer Science | Principle/ Method | is_prerequisite_ of K16; comprises K05, K13, K14, K17 |
| K16 | System Integration and Debugging | Computer Science / Electronics | Skill/Process | is_applied_in K21 |
| K17 | Vehicle Lateral Control | Vehicle Engineering / Artificial Intelligence | Principle/ Method | is_component_ of K15; requires K11 |
| K18 | On-board Diagnostic System | Vehicle Engineering / Electronics | Case/ Situational | utilizes K06 |
| K19 | Fault Diagnosis Strategy | Vehicle Engineering | Principle/ Method | is_applied_in K18 |
| K20 | Longitudinal Dynamics Control | Vehicle Engineering | Principle/ Method | requires K11 |
| K21 | Real-Vehicle Road Testing Process | Vehicle Engineering / Computer Science | Skill/Process | evaluates K15, K16 |
| K22 | Functional Safety Standards | Vehicle Engineering / Management | Conceptual | constrains K15, K21 |
| K23 | Data Privacy Regulations | Law / Computer Science | Conceptual | constrains K24 |
| K24 | On-board Data Management | Computer Science | Skill/Process | is_applied_in K15 |
| K25 | Embedded System Development | Electronics / Computer Science | Skill/Process | is_prerequisite_of K05, K16 |
| K26 | Real-Time Operating System | Computer Science | Conceptual | is_prerequisite_of K25 |
| K27 | Path Planning Algorithm | Artificial Intelligence / Computer Science | Principle/ Method | is_component_of K14 |
| K28 | System Redundancy Design | Electronics / Vehicle Engineering | Principle/ Method | is_applied_ in K15; addresses K22 |

*Table B2. Definitions of Semantic Relationship Types in the Knowledge Graph*

| Relationship Name | Definition & Description | Example (from the "Intelligent Connected Vehicle" Case) | Category |
|---|---|---|---|
| **is_ prerequisite_ of** | ndicates that mastering one knowledge component is a prerequisite for learning another, forming a foundational-to-advanced relationship. | K03 Convolutional Neural Network is_prerequisite_ of K08 Deep Learning Framework Usage | Knowledge Dependency |
| **is_applied_in** | Indicates that a theory, method, or technique is applied within a specific scenario, case, or module. | K04 SLAM Algorithm is_ applied_in K13 Environmental Perception Module | Functional Application |
| **is_ component_of** | Indicates that a knowledge component is an integral part of a larger system or architecture. | K13 Environmental Perception Module is_ component_of K15 Software System Architecture | Structural Composition |

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| | | | |
|---|---|---|---|
| **is_ synergistic_ with** | Indicates that two knowledge components have synergistic, complementary, or enhancing effects when solving problems. | K02 V2X Communication is_ synergistic_with K09 Multi-sensor Calibration | Synergistic Interaction |
| **utilizes** | Indicates that a component, to realize its function, needs to invoke or use specific resources, tools, or capabilities provided by another component. | K07 Autonomous Driving Visual Perception utilizes K03 Convolutional Neural Network | Functional Application |
| **integrates** | Indicates that a module or system unifies multiple distinct knowledge components into a cohesive whole. | K13 Environmental Perception Module integrates K01, K04, K07 | Structural Composition |
| **comprises** | The inverse relationship of is_ component_of, describing the constituent sub-components from a top-down perspective. | K15 Software System Architecture comprises K05, K13, K14, K17 | Structural Composition |
| **requires** | Emphasizes a mandatory dependency or need of one component on another for its operation or implementation. | K17 Vehicle Lateral Control requires K11 Vehicle Dynamics | Knowledge Dependency |
| **evaluates** | Indicates that a process, method, or tool is used to test, examine, or assess the performance and effectiveness of another component or system. | K21 Real-Vehicle Road Testing Process evaluates K15, K16 | Verification & Evaluation |
| **constrains** | Indicates that a standard, specification, or regulation imposes constraints and limitations on the design, implementation, or application of other components. | K22 Functional Safety Standards constrains K15, K21 | Constraint & Regulation |
| **addresses** | Indicates that a design solution or technical measure aims to meet, solve, or respond to specific requirements, constraints, or challenges. | K28 System Redundancy Design addresses K22 Functional Safety Standards | Constraint & Regulation |

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