This is an innovative research on AI-empowered project-based teaching reform of "Advanced Mathematics"

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Abstract: *The development of artificial intelligence technology provides a new technological path for the teaching reform of project-based learning in Advanced Mathematics. This research focuses on the theoretical reconstruction and mechanism design of AI-empowered project-based teaching in Advanced Mathematics, and it carries out discussions from three levels. At the theoretical level, this research analyzes the intelligent transformation characteristics of project-based teaching in Advanced Mathematics, explains the mechanism of AI embedding into mathematical cognitive construction, and constructs a framework for a human-machine collaborative learning ecosystem. At the mechanism level, this research establishes a semantic association model between knowledge units and project themes, designs a difficulty adaptive adjustment strategy based on student performance data, and forms an intelligent matching path between multimodal resources and project tasks. At the intervention level, this research realizes the tracking and representation of mathematical thinking trajectories, establishes an automatic identification mechanism for reasoning obstacles, and forms a closed-loop system for personalized scaffolding delivery and optimization of inquiry depth. This research aims to promote the paradigm shift of project-based teaching in Advanced Mathematics from experience-driven to data-driven.*

Keywords: *Advanced Mathematics; Project-Based Teaching; Knowledge Graph; Cognitive Load; Intelligent Intervention; Adaptive Learning*

Introduction

Advanced Mathematics serves as a foundational course for science and engineering majors, and its teaching objectives cover the dual dimensions of knowledge transmission and cognitive cultivation. Project-based teaching provides learners with an effective path for cognitive construction by embedding mathematical knowledge into authentic problem contexts. However, traditional implementation models face three major limitations: project content relies on experience-based presupposition, which makes it difficult to adapt to individual cognitive differences; process monitoring remains at the stage of periodic assessment, which fails to capture the micro-trajectories of cognitive evolution; resource provision exhibits static characteristics, which lacks dynamic adaptation to task demands. The introduction of artificial intelligence technology offers a new path for addressing the above difficulties. The collection and analysis of learning process data by intelligent systems drive teaching decisions toward data-driven approaches, the structured representation of mathematical concepts through knowledge graphs enables the dynamic generation of project content, and the real-time feedback mechanism facilitates the immediate identification of cognitive obstacles, thereby realizing personalized interventions. This research focuses on the innovative issues of AI-empowered project-based teaching in Advanced Mathematics, and it carries out discussions from three levels: theoretical reconstruction, mechanism design, and process intervention, in order to provide support for the transformation of teaching models.

1. Theoretical Reconstruction of Intelligent Technology Embedded in Project-Based Teaching of Advanced Mathematics

1.1 The Evolution and Intelligent Turn of the Project-Based Teaching Paradigm in Advanced Mathematics

The evolution process of project-based teaching in Advanced Mathematics presents a progressive feature from tool assistance to structural reshaping. In the early stage, project-based teaching mainly existed as an application scenario for mathematical knowledge, and project design was carried out around a predetermined sequence of knowledge points, with technical tools only serving marginal functions such as calculation assistance or result visualization. With the development of learning theories and the penetration of digital technologies, project-based teaching gradually shifts from an auxiliary model to an integrated model, and the degree of integration between project themes and mathematical content deepens. However, the underlying logic of instructional design remains dominated by a presuppositional framework.

The intelligent turn marks a new stage of paradigm reconstruction for project-based teaching. The core of this turn lies in the transition of the project generation mechanism from static presupposition to dynamic adaptation, and the intelligent system adjusts the project difficulty, the recommendation of mathematical tools, and the progressive logic of tasks in real time based on the learner's cognitive state data. The allocation mode of teaching decision-making authority accordingly undergoes a structural change, and some experience-driven decision-making functions migrate into a data-driven collaborative framework. Thus, project-based teaching in Advanced Mathematics acquires an adaptive capability grounded in individual cognitive characteristics[1].

1.2 Mechanism Analysis of Artificial Intelligence Technology Embedded in Mathematical Cognitive Construction

The mechanism of artificial intelligence technology embedded in mathematical cognitive construction is rooted in the essential characteristics of Advanced Mathematics learning. Advanced Mathematics cognition involves the repeated coordination of symbolic manipulation and visual imagination, and abstract concepts such as limits and continuity require the transformation through multiple representations to achieve internalization. The provision of cognitive scaffolds in traditional teaching environments is limited by the teacher's individual experience and the spatiotemporal boundaries of the classroom, which makes it difficult to achieve fine-grained tracking and intervention in the learner's cognitive process.

Intelligent technology represents and regulates the mathematical cognitive process through algorithmic models, and its embedding path is manifested in the dynamic adaptation of cognitive pathways and the intelligent construction of conceptual networks. The system collects the learner's behavioral data during the project-solving process, models the cognitive state in combination with the knowledge graph, and dynamically adjusts the presentation order and abstraction level of mathematical concepts in the project tasks. Regarding the difficulty of cultivating abstract thinking, intelligent technology helps learners establish the connection between symbols and meanings through multimodal representation transformation and analogical reasoning support, thereby promoting the lateral transfer of mathematical ideas.

1.3 Construction of a Mathematics Project-Based Learning Ecosystem from the Perspective of Human-Machine Collaboration

The mathematics project-based learning ecosystem from the perspective of human-machine collaboration is a dynamic adaptive system composed of learners, teachers, intelligent systems, and mathematical knowledge resources. The construction logic of this ecosystem emphasizes the bidirectional construction among all elements: the learner's behavioral data feeds back into system optimization, and the teacher's role shifts from knowledge importer to regulator of the learning process. The healthy operation of the ecosystem depends on the intelligent system's fusion processing of multi-source information and its precise intervention at critical junctures.

The construction of the learning ecosystem is based on the structured representation of mathematical knowledge. The intelligent system, through the semantic parsing of curriculum standards and the deep learning of textbook content, constructs a knowledge graph that covers the core concepts of Advanced Mathematics and establishes multi-dimensional associations between knowledge units and the project theme library. During the project-based learning process, the system analyzes the learner's problem-solving process and resource browsing trajectory in real time, identifies common problems and individual differences, and regulates project difficulty as well as collaboration and division of labor, thereby making mathematics project-based learning a cognitive development system with self-organizing characteristics.

2. Dynamic Generation Mechanism of Mathematics Project Content Based on Knowledge Graph

2.1 Semantic Association Model Between Knowledge Units of Advanced Mathematics and Project Themes

The knowledge system of Advanced Mathematics has a rigorous logical hierarchy and a complex associative structure. Knowledge units not only have sequential prerequisite dependencies, such as limits serving as the foundation for continuity and derivatives, but also contain lateral analogical transfer paths, such as the echo of ideas and methods between linear algebra in finite-dimensional spaces and functional analysis in infinite-dimensional spaces. As the application carrier of mathematical knowledge, the design of project themes needs to accurately map the intrinsic logic of specific knowledge combinations while maintaining the authenticity and integrity of the problem context, so that learners can naturally touch the essential connotations of mathematical concepts during project inquiry. Establishing a semantic association model between knowledge units and project themes is the foundational work for achieving dynamic generation of project content[2].

The construction of the semantic association model relies on the formal representation of mathematical concept ontologies and their relationships through knowledge graph technology. Through the in-depth analysis of Advanced Mathematics textbooks, curriculum standards, and classic project cases, this model extracts core concept nodes such as limits, derivatives, integrals, series, and differential equations, as well as multiple relationship types including definitions, theorems, properties, methods, and applications, thereby forming a knowledge network covering the disciplinary backbone. On this basis, this model deconstructs each project in the project theme library into problem context elements and mathematical structure elements: the former describes the realistic background and problem domain characteristics of the project, while the latter characterizes the mathematical operations, reasoning, and modeling processes implicit in the project. Through semantic similarity calculation and concept co-occurrence analysis, this model establishes many-to-many mapping relationships between project themes and knowledge units. This mapping not only covers explicit knowledge point correspondences but also includes implicit associations of thinking methods, such as associating optimization problems with both extremum theory and convex analysis, so that project themes can carry the multi-dimensional connotations of mathematical knowledge and support the integrated application across units.

2.2 Adaptive Adjustment Strategy for Project Difficulty Based on Student Performance Data

The setting of project difficulty directly affects the learner's cognitive load and learning motivation. Excessive difficulty leads to frustration and thought blocking, while insufficient difficulty fails to stimulate deep inquiry. In traditional teaching, the project difficulty relies on the teacher's experience for overall setting, which makes it difficult to accommodate the cognitive differences among individuals within a group. The adaptive adjustment strategy based on student performance data aims to maintain a dynamic match between project difficulty and the learner's current cognitive level.

The realization of the adaptive adjustment strategy is based on the continuous collection and modeling of student performance data. The learner's micro-behavioral data generated during the project process, such as problem-solving time, error types, help-seeking frequency, and exploration paths, are input into the cognitive diagnostic model after feature extraction, thereby forming a quantitative representation of the learner's knowledge mastery status and thinking quality. Based on this representation result, the system dynamically adjusts the mathematical depth, step complexity, and inquiry openness of the current project. The adjustment mechanism follows the principle of the zone of proximal development. Under the premise of ensuring that the core mathematical structure of the project remains unchanged, the mechanism achieves fine-grained regulation of difficulty by changing numerical parameters, adding or reducing intermediate hints, and expanding problem boundaries, so that the learner is always in a cognitive state of moderate challenge.

2.3 Intelligent Matching Path Between Multimodal Resources and Mathematics Project Tasks

In project-based learning of Advanced Mathematics, learners need to call upon multiple types of resources to support problem solving, including conceptual explanations from text handouts, reasoning demonstrations from video lectures, visual simulations from dynamic presentations, and parameter explorations from interactive simulations, among other modalities of learning materials. The richness and heterogeneity of resources provide multiple channels for learning, but they also bring the problems of information overload and selection confusion, as learners often find it difficult to locate the resources that best match their immediate needs within a limited time. The goal of the intelligent matching path is to accurately push the most appropriate multimodal resources based on the characteristics of the project task and the learner's real-time needs, thereby reducing cognitive load while improving resource utilization efficiency[3].

The realization of intelligent matching relies on the bidirectional alignment between resource semantic annotation and user demand modeling. First, this approach performs structured processing on multimodal resources and extracts metadata such as the mathematical knowledge points associated with each resource, the applicable project stage, the presented cognitive function, and the expected learning effect. Meanwhile, during the execution of the project task, this approach identifies the learner's type of resource demand, whether it belongs to concept understanding, method mastery, or application expansion, by analyzing the learner's current behavior and potential confusion. The matching algorithm comprehensively considers task requirements, knowledge status, learning preferences, and resource characteristics, calculates the degree of fit between resources and demands, and achieves intelligent push of the optimal resource sequence selected from the massive resource library, thereby providing precise support for the smooth progress of mathematics project tasks.

3. Intelligent Intervention in the Mathematics Project Process Under Cognitive Load Regulation

3.1 Tracking and Representation of Learners' Mathematical Thinking Trajectories in the Project Process

In project-based learning of Advanced Mathematics, the learner's thinking activities are implicit in the continuous process of problem solving, and they exhibit complex characteristics of dynamism, nonlinearity, and multimodal interweaving. In traditional teaching environments, teachers' perception of the thinking process depends on the presentation of interim results and observations of limited duration, and thus it is difficult for them to capture the complete trajectory of the emergence and evolution of thinking. The fine-grained tracking and structured representation of mathematical thinking trajectories serve as the prerequisite for achieving intelligent intervention in the process. The presentation of thinking trajectories not only concerns the recording of behavioral sequences but also involves the externalization and mapping of the deep structure of mathematical cognition.

The tracking of thinking trajectories relies on the intelligent system's collection and fusion of multi-source behavioral data during the project process. Every operation of the learner in the mathematics project, including symbol input, formula transformation, graph drawing, parameter adjustment, and information retrieval, is recorded as a time-series data sequence. The system performs deep analysis on these data through a cognitive computing model and extracts key features that reflect the thinking path, such as the tendency of problem-solving strategy selection, the derivation order of intermediate conclusions, and the transformation patterns between different representational forms. The introduction of eye-tracking and screen recording technologies further enriches the data sources, allowing the system to capture the patterns of gaze shifts between mathematical symbols and graphics, thereby providing finer support for the reconstruction of thinking trajectories[4].

On this basis, this approach constructs a topological structure diagram of the thinking trajectory and visualizes the learner's cognitive path from the initial problem state to the final solution. This representation method not only displays the final outcome but also presents the key nodes and turning points in the thinking process, including effective reasoning paths and ineffective exploratory branches. The representation of the thinking trajectory also involves the marking of the learner's metacognitive behaviors, such as self-correction, retrospective verification, and strategy adjustment. The externalization of these higher-order thinking activities provides a more complete cognitive picture for subsequent intervention decisions. Through cluster analysis of a large number of thinking trajectories, the system can also summarize the typical thinking patterns of learners with different cognitive styles, thereby laying the foundation for the model training of personalized interventions.

3.2 Automatic Identification of Mathematical Reasoning Obstacles Based on Real-Time Feedback

In the process of mathematics projects, learners' reasoning activities often encounter obstacles, which manifest in different forms such as interruption of thinking, circular reasoning, misuse of concepts, or logical leaps. The timely discovery and accurate localization of these obstacles are the key links to ensure the smooth progress of the project and the development of cognition. The automatic identification mechanism based on real-time feedback can capture abnormal signals during the continuous monitoring of thinking trajectories, thereby achieving instant diagnosis of reasoning obstacles. The accuracy of the diagnosis directly affects the pertinence and effectiveness of subsequent intervention measures.

The operation of the identification mechanism relies on the algorithmic modeling of mathematical reasoning norms. The intelligent system incorporates a rule base of Advanced Mathematics reasoning and a typical error pattern base, and it performs real-time comparisons between the learner's reasoning steps and the normative paths, thereby locating possible obstacle nodes through difference analysis. The construction of the rule base is based on the analysis of the logical system of Advanced Mathematics, covering normative requirements such as the order-preserving property of limit operations, the applicable conditions of the mean value theorem for derivatives, and the discriminant criteria for series convergence. The error pattern base, through the mining of historical learning data, summarizes frequently occurring types of reasoning deviations, such as the omission of the chain rule in the differentiation of composite functions and the misjudgment of direction in surface integrals.

For multi-step reasoning in complex projects, the system adopts the Hidden Markov Model or the Graph Neural Network to perform state transition analysis on the thinking trajectory, and it identifies the key positions where the reasoning chain breaks or where circular wandering occurs. Such models are capable of processing the temporal dependencies in the thinking path and distinguishing between temporary confusion and persistent obstacles. The identification results include not only the location information of the obstacle points but also a preliminary judgment of the obstacle type, such as concept confusion, inappropriate methods, or representation transformation errors. The system simultaneously calculates the confidence level of the identification. For obstacle points with low confidence, the system adopts a continuous observation strategy to avoid premature interference with the learner's autonomous exploration. The identification information and the thinking trajectory data together constitute the input basis for intervention decisions[5].

3.3 Personalized Scaffolding Push and Dynamic Optimization of Mathematics Inquiry Depth

The key step after identifying reasoning obstacles is to provide learners with appropriate support to overcome the obstacles and maintain the continuity of inquiry. The push strategy of personalized scaffolding needs to comprehensively consider the learner's cognitive state, the type of obstacle, and the mathematical structure of the project task, and it needs to achieve precise support without excessive intervention. The content forms of the push include various types such as prompting questions, analogy cases, step-by-step guidance, and concept micro-lectures, and their common goal is to activate the learner's metacognitive monitoring and self-regulation ability. The design of the scaffolding follows the principle of gradual release: it provides minimal intervention at the initial stage and gradually increases the level of support as the duration of the obstacle extends.

While pushing the scaffolding, the system continuously monitors the learner's subsequent reactions to evaluate the intervention effect, and it dynamically adjusts the inquiry depth of the project accordingly. If the learner can independently advance to deeper mathematical reasoning after receiving support, the system moderately increases the openness and complexity of the task. If the learner is still in a state of cognitive overload, the system temporarily narrows the inquiry boundary and provides more structured support. The dynamic optimization of inquiry depth involves not only the adjustment of task difficulty but also the change in the degree of openness of mathematical problems, and the progressive process from closed-form calculation to open-ended modeling can be flexibly switched according to the learner's real-time state.

This real-time feedback-based dynamic optimization mechanism of depth ensures that the mathematics project process always remains within a cognitive interval that is both bearable and challenging for the learner. The system continuously monitors the learner's flow state indicators, such as operation fluency, error rate changes, and help-seeking frequency, and it implicitly assesses cognitive load. When the system detects persistently inefficient exploration, it actively provides scaffolded guidance. When the system observes an increase in thinking activity, it timely removes support to promote the development of autonomy. The entire intervention process forms a closed-loop structure of monitoring-diagnosis-intervention-re-monitoring. This structure not only avoids thought stagnation caused by excessive load but also prevents superficial thinking caused by excessive simplification, ultimately achieving the orderly development and gradual improvement of mathematical thinking ability.

Conclusion

This research systematically explores the core issue of AI-empowered project-based teaching reform in Advanced Mathematics from three levels: theoretical reconstruction, mechanism design, and process intervention. At the theoretical level, this research reveals the intelligent transformation characteristics of project-based teaching in Advanced Mathematics from tool assistance to structural reshaping, analyzes the intrinsic mechanism of artificial intelligence technology embedded in mathematical cognitive construction, and constructs the basic framework of a mathematics project-based learning ecosystem from the perspective of human-machine collaboration. At the mechanism level, this research establishes a semantic association model between knowledge units of Advanced Mathematics and project themes, proposes an adaptive adjustment strategy for project difficulty based on student performance data, designs an intelligent matching path between multimodal resources and mathematics project tasks, and forms a technical solution for the dynamic generation of project content. At the process intervention level, this research achieves the tracking and representation of learners' mathematical thinking trajectories in the project process, establishes an automatic identification mechanism for mathematical reasoning obstacles based on real-time feedback, and realizes the dynamic optimization of personalized scaffolding push and mathematics inquiry depth, forming a closed-loop structure of monitoring-diagnosis-intervention-re-monitoring. The integrated application of the above three levels promotes the transformation of project-based teaching in Advanced Mathematics from an experience-driven paradigm to a data-driven paradigm, providing theoretical support and practical pathways for the innovation of mathematics education in the context of intelligence.

At the intervention level, this research realizes the tracking and representation of learners' mathematical thinking trajectories in the project process, establishes an automatic identification mechanism for mathematical reasoning obstacles based on real-time feedback, and forms a closed-loop system for personalized scaffolding push and dynamic optimization of mathematics inquiry depth. The above research provides theoretical support and technical pathways for the paradigm shift of project-based teaching in Advanced Mathematics from experience-driven to data-driven. Subsequent research can be deepened in the following directions: first, optimizing the algorithmic accuracy of the mathematical cognitive diagnosis model to enhance the recognition capability for complex reasoning processes; second, expanding the construction of an interdisciplinary project theme library to deepen the integration of mathematical knowledge with engineering and scientific problems; third, exploring the integrated application of multimodal learning analytics technologies to achieve comprehensive perception of learners' cognitive and affective states; fourth, conducting long-term tracking studies of intelligent intervention strategies to verify their sustained impact on the development of mathematical thinking ability.

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