

Research on the Mechanism of Learning Intervention and Path Optimization Based on Competency Map-Driven Student Digital Twins

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Abstract: Against the background of the deepening transformation of digital education and the prominent structural contradictions between talent supply and demand, the traditional higher education model can no longer meet the diverse learning needs of students nor the market's expectations for interdisciplinary talents. Based on the construction of students' competence map, this study takes the digital intelligence-driven Digital Twin of Students (DTS) as the core element of the learning architecture in institutions of higher education, and systematically explores its conceptual framework, operational mechanism, platform deployment, as well as its functions in students' learning intervention and path optimization. The research indicates that the Digital Twin of Students integrates multi-dimensional dynamic data of students; relying on AI evaluation and decision-making controllers, it achieves the transformation of learning intervention from "extensive coverage" to "precision drip irrigation", constructs a learning path optimization system featuring "goal anchoring-dynamic adaptation-continuous iteration", and ensures practical efficiency through modular deployment and standardized technologies. This system effectively resolves the structural contradictions between the supply of talent training and market demand, promotes the construction of a personalized learning ecosystem, and provides theoretical support and practical approaches for the digital transformation of talent training in colleges and universities, the improvement of students' core literacy, and the accurate alignment between talent supply and demand.

Keywords: Student Digital Twin; Competence Map; Learning Intervention; Path Optimization.

1. Introduction

In February 2023, Huai Jinpeng, Minister of Education of China, stated at the World Digital Education Conference that digital transformation serves as a crucial carrier and orientation for the transformation of global education. What remains unalterable in the digital transformation of education is its social mission, whereas the aspects requiring reform or transformation involve the utilization of digital technologies to reconstruct learning modes and educational approaches, as well as to optimize educational governance and decision-making [1]. Against the backdrop of the accelerated iteration of digital technologies, the dynamic evolution of labor market demands, and the growing prominence of global development uncertainties, the structural contradiction between the labor market's requirements for the adaptability of high-quality talents' knowledge and skill systems and the supply of talent cultivation in higher education has become increasingly prominent. With the deepening of digital education transformation and the prominent contradiction between talent supply and demand, the traditional higher education model can no longer adapt to the diverse learning needs of students and the market's expectations for interdisciplinary talents. There is a growing recognition that the construction of a personalized, flexible, and competence map-oriented learning ecosystem is of vital importance for helping students stand out in the rapidly changing talent competition [2].

Based on the construction of students' competence map, this study takes the digital intelligence-driven Digital Twin of Students (DTS) as the core element of the future learning architecture for college students. The Digital Twin of Students is defined as a continuously evolving digital

representation of students, integrating real-time academic data, behavioral signals, competence levels, and career preferences [3]. It has dual functions as a diagnostic tool and an improvement engine, supporting two-way interaction: on the one hand, artificial intelligence algorithms enrich the content of the Digital Twin of Students based on data from the students' competence map; on the other hand, the Digital Twin of Students in turn provides a scientific basis for generating and adjusting personalized, competence-oriented learning paths.

2. Conceptual Framework of Students' Competence Map

The composition of the students' competence map is a full-process closed-loop system of "data-knowledge-application". Each layer collaborates and progresses step by step to achieve a complete transformation from raw data input to knowledge value realization and then to competence formation, providing systematic knowledge support for discipline teaching, learning, and scientific research. This architecture takes the multi-source heterogeneous data layer as the data base, integrating three types of raw data: structured, semi-structured, and unstructured, solving the problems of scattered discipline data and inconsistent formats, and providing sufficient raw materials for subsequent knowledge processing. The knowledge acquisition layer relies on natural language processing technology to extract core disciplinary concepts from heterogeneous data, complete entity recognition and relationship extraction, and convert unstructured and semi-structured data into initial "entity-relationship" knowledge units, laying the foundation for the construction of the competence map. The knowledge fusion

layer resolves redundancy, conflicts, and heterogeneity of multi-source knowledge through Schema fusion, entity alignment, and entity linking, eliminates knowledge ambiguity, and forms a standardized knowledge set with consistent logic and unified structure. The knowledge storage layer adopts a graph database to store "entity-relationship-attribute" triple knowledge, and combines quality control methods such as consistency check and integrity detection to achieve efficient storage, retrieval, and management of knowledge, providing a reliable carrier for knowledge reasoning. The knowledge reasoning layer expands knowledge content, optimizes the knowledge system, enriches knowledge dimensions, and improves knowledge availability through knowledge completion, knowledge denoising, and logical reasoning. As the core of value realization, the knowledge empowerment layer transforms the competence map into disciplinary scenario application services such as semantic search, intelligent recommendation, intelligent question answering, and explanation generation, connects with various actual needs, and realizes the effective realization of knowledge value. The entire architecture is closely connected and works collaboratively to build a standardized, efficient, and reusable disciplinary knowledge service system, demonstrating the core supporting role of the competence map in the disciplinary field [4].

3. Conceptual Framework of the Digital Twin of Students

The Digital Twin of Students is a core architectural element for modern colleges and universities to transform towards adaptive, personalized, and competence-oriented learning systems. This study defines the connotation, structure, and operational role of the Digital Twin of Students. The Digital Twin of Students is defined as a stateful, artificial intelligence-enhanced, and semantically structured computational entity that can map the evolutionary records of students throughout their academic careers. Formally, the Digital Twin of Students can be expressed as a multi-layer tuple: $DTS(s,t) = \langle As(t), Cs(t), Ls(t), Rs(t), Es(t) \rangle$. Among them, for student s in student set S at time t : academic performance and learning history are represented by $As(t)$; competence achievement level is represented by $Cs(t)$; learning preferences and behaviors are represented by $Ls(t)$; career interest and labor market adaptability are represented by $Rs(t)$; social-emotional and engagement signals are represented by $Es(t)$. This five-component model ensures that the Digital Twin of Students evolves dynamically over time, supporting both retrospective evaluation of learning paths and forward-looking planning. The Digital Twin of Students has reflective and diagnostic functions. In a continuous cycle, the Digital Twin of Students systematically monitors and interprets students' states in multiple dimensions (such as academic performance and competence level). When there is a significant deviation between students' academic performance, competence level, or other dimensions and the expected goals, the system will automatically reflect, adjust, and recommend remedial measures, and generate an adaptive path consistent with students' goals based on reflection to guide students to achieve their established goals.

4. Operational Mechanism of the Digital Twin of Students Based on the Competence Map

The Digital Twin of Students has the functions of both an AI state evaluator and an AI decision-making controller. Given the target competence profile of students for future positions, the Digital Twin of Students can support the construction of adaptive learning paths.

The Digital Twin of Students $DTS(s,t) = \langle As(t), Cs(t), Ls(t), Rs(t), Es(t) \rangle$ can be represented as a mathematical state space model of student learning [5]. Among them, artificial intelligence (AI) plays the role of evaluator and controller in the feedback loop. The dynamic operation of the Digital Twin of Students can be divided into stages such as data input, state evaluation, path planning, and execution and feedback (as shown in the figure one). In this model, students interact continuously with the educational environment, generating various types of data input over time, including academic records, behavioral logs, evaluation results, and external signals such as career goals or engagement indicators.

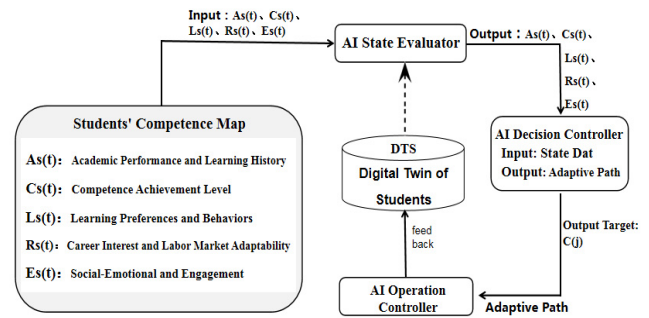


Figure 1. Digital Twin of Students Based on Competence Map

This system has the function of a "reflection-diagnosis" cycle. The Digital Twin of Students framework integrates the students' competence map, which includes both historical records (such as previously learned courses, grades, and achieved competence certifications) and currently dynamically updated information (such as engagement level, real-time academic performance, and behavioral indicators). By integrating past and current data, the students' competence map ensures that students' academic states are not static but continuously evolving, enabling the Digital Twin of Students to provide knowledge, competence, and emotions that reflect long-term academic development patterns and real-time learning needs. The core of this architecture is the Digital Twin of Students itself. As a dynamic and continuously updated virtual model, it can capture each student's academic state, behavioral patterns, engagement level, and changing goals in real time. The system operates through a structured process of AI evaluation, control, and feedback, with full collaboration among three artificial intelligence controllers working at different abstraction levels:

The process mechanism starts with the AI state evaluator, which extracts multi-modal input data from the students' competence map, including academic performance and learning history data $As(t)$, competence achievement level $Cs(t)$, learning preferences and behaviors $Ls(t)$, career interest and labor market adaptability $Rs(t)$, and social-emotional and engagement $Es(t)$. It converts raw input into a structured data representation of the learner's current state, updates the Digital Twin of Students in real time, and provides a basis for AI intelligent decision-making. Once the student's current

state is evaluated, the AI decision-making controller generates a personalized learning trajectory consistent with the student's long-term academic or career goals. Using the current state vector and the expected target $C(j)$ of a specific course or learning module, it calculates and optimizes an adaptive learning path suitable for the student's academic development. This path is constructed through algorithmic planning technologies (such as reinforcement learning or graph-based traversal algorithms) to make up for the identified competence deficiencies in the Digital Twin of Students in the most effective way that conforms to teaching rules. At the same time, at the micro level, to better implement this adaptive learning path, the Digital Twin enables an AI controller to monitor the student's real-time progress and implement personalized strategies. It processes continuous feedback from the Digital Twin of Students and the student's actual engagement, provides operable suggestions (such as dynamic content adjustment, automatic reminders, or chatbot intervention), and ensures the adherence to the learning path and learner support.

Secondly, as an AI operation controller, it enables the system to respond timely to changes in students' learning behaviors or external disturbances. At the micro level, intervention measures are reflected in refined actions targeting individual learners. For example, the Digital Twin of Students may assign additional practical tasks to strengthen weak competences, recommend supplementary reading materials or online multimedia resources according to students' preferred learning styles, adjust the difficulty of subsequent exercises based on performance trends, or initiate multi-collaborative tasks when engagement signals decline. These micro-level diagnoses ensure that the adaptation process is real-time, personalized, and responsive to the changing needs of learners.

In summary, the "reflection-diagnosis" cycle in the Digital Twin of Students is a continuous adaptation process. The system can evaluate student attributes, generate insights, and formulate personalized intervention measures. This process ensures that the student's learning path not only responds to academic performance but also adapts to motivation, preferences, and career goals, thereby realizing the core adaptability principle of the Digital Twin of Students framework. These components together form a closed-loop circuit of the Digital Twin of Students driven by an artificial intelligence control architecture, enabling the Digital Twin to evolve continuously and guide students to experience a personalized, adaptive, and competence-aligned educational experience.

5. Platform Deployment of the Digital Twin of Students Based on the Competence Map

The figure two shows the modular deployment architecture of the Digital Twin of Students platform, indicating how its components coordinate operations in different operational layers and deployment environments. The deployment architecture design of the Digital Twin of Students platform adopts a hybrid modular deployment system, integrating institutional data sources, artificial intelligence services, and user interfaces from three interconnected areas: the on-premises deployment area, the hybrid deployment area, and the cloud-based Digital Twin platform.

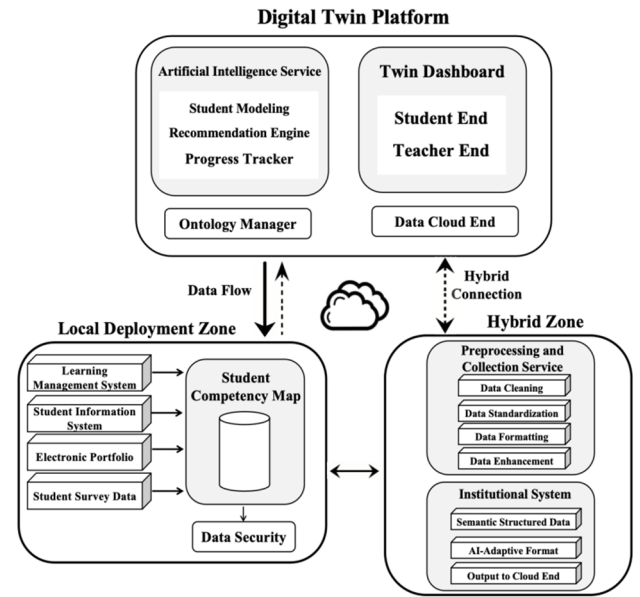


Figure 2. Platform Deployment of the Digital Twin Based on the Competence Map

In the on-premises deployment area, system data such as learning management systems, student information systems, e-portfolios, and student survey data constitute a rich multi-modal data stream. These data will not only be securely collected but also aggregated into the students' competence map, which serves as a unified storage for structured and unstructured data. The data privacy and security layer in the map ensures that data is securely protected and supervised to prevent the leakage of students' private data.

The raw data, through the composed students' competence map, is then transmitted to the hybrid area, where preprocessing and collection services perform basic tasks such as data cleaning, data standardization, data formatting, and data enhancement, converting data sets in institutional systems into semantically structured data suitable for AI-driven analysis, and then outputting them to the cloud in an AI-adapted format. This intermediate layer serves as a secure and efficient bridge between institutional systems and the cloud.

The core of the system is the cloud-based Digital Twin platform, relying on artificial intelligence advancement engines and semantic services required for student data modeling, decision-making, and interaction. In this layer, the student data modeling module continuously updates students' digital states using input data; the recommendation engine generates adaptive learning paths aligned with each student's goals; the progress tracker monitors students' competence progress throughout the learning process; the ontology manager links input data with semantic frameworks (such as $As(t)$, $Cs(t)$, $Ls(t)$, $Rs(t)$, $Es(t)$) and supports interpretable reasoning and intelligent queries; the Twin Dashboard provides dedicated interfaces for students and teachers: the student end receives real-time personalized feedback, trajectory updates, and alerts from the Digital Twin; the teacher end obtains real-time class-level insights, interventions, and curriculum mapping tools, enabling real-time macro adjustments to students' learning progress and states.

Although the above figure shows the deployment of the Digital Twin of Students platform at the conceptual level, the ultimate goal of this architectural design is to be truly

implemented in practical scenarios and exert its maximum functional effect. In practice, the deployment of the Digital Twin of Students relies on modular and containerized infrastructure, where each functional block (data integration, analysis, competence map, and user interface) operates as an independent service. These services communicate through secure Application Programming Interfaces (APIs) and Message Brokers to ensure interoperability and scalability across diverse institutional systems.

The deployment of the Digital Twin of Students can be carried out in a hybrid environment, combining students' competence map data and cloud-based AI services. Through Learning Tools Interoperability (LTI), a "universal interface" between learning systems and teaching tools, and xAPI (Experience API), an open technical standard for tracking, recording, and sharing learners' full-scenario learning experiences, various learning behavior data inside and outside the classroom, online and offline, are captured to provide comprehensive data support for the Digital Twin of Students. These standards promote integration with existing learning management systems, enabling the functions of the Digital Twin of Students to be seamlessly embedded into the existing digital learning ecosystem. This layered and standard-based deployment design provides flexibility, fault isolation, and progressive adoption capabilities while maintaining compliance with privacy and data security requirements.

6. Research Conclusion

The student digital twin (DTS) based on competency maps breaks the "one-size-fits-all" intervention model and static path design logic in traditional higher education. Relying on the closed-loop mechanism of "data-driven-precise diagnosis-dynamic optimization", it transforms the knowledge and competency-related data of student competency maps into implementable learning intervention strategies and personalized path plans, realizing the precision of learning intervention, the dynamics of path design and the targeting of competency cultivation. It effectively solves the structural adaptation problems between supply and demand, teaching and learning in talent cultivation, and provides systematic support for the improvement of students' core literacy.

6.1. Transformation of Learning Intervention from "Generalized Coverage" to "Precision Customization"

With the student competency map as the core data support base, the student digital twin (DTS) constructs a whole-process system for precise identification of intervention needs, personalized matching of intervention strategies, and real-time feedback of intervention effects, realizing the transformation of learning intervention from "general coverage" to "precision irrigation". Relying on the AI state evaluator, the digital twin system integrates multi-dimensional heterogeneous data such as students' competency achievement level $Cs(t)$ and academic performance $As(t)$. With the knowledge reasoning technology of competency maps, it conducts multi-dimensional comparison with the preset target competency thresholds, accurately locates students' weak links and core competency gaps in knowledge acquisition, skill application, thinking habits, etc., clarifies the specific types (such as disconnected knowledge links, unskilled skill application, incoherent

logical thinking) and quantitative degrees of competency deficiencies, effectively avoiding the prominent drawbacks of "blind implementation and general intervention" in traditional learning interventions.

In response to different types and degrees of intervention needs, the digital twin relies on the AI decision controller to generate differentiated and targeted intervention plans: for students with weak knowledge, it accurately pushes basic knowledge point resources, layered targeted exercises and personalized Q&A services highly related to the competency map to consolidate the knowledge base; for students with insufficient skills, it matches suitable practical learning modules and virtual simulation training scenarios to strengthen the transformation from knowledge to practical skills and improve skill application ability; for students with insufficient learning motivation, combined with socio-emotional and engagement data $Es(t)$, it activates students' endogenous learning motivation through collaborative task design, phased goal incentives, personalized feedback guidance and other methods. Meanwhile, in the process of intervention implementation, it collects real-time dynamic data of students' learning behaviors $Ls(t)$, dynamically iterates and adjusts intervention strategies and implementation paths, and constructs a closed-loop mechanism of "diagnosis-intervention-feedback-optimization" to ensure that intervention effects directly reach the core of competency improvement and maximize intervention efficiency.

6.2. Construction of a "Goal Anchoring–Dynamic Adaptation–Continuous Iteration" Learning Path Optimization System

Guided by competency maps, the digital twin constructs a learning path optimization system of "goal anchoring-dynamic adaptation-continuous iteration", realizing the synchronization of path design with student development and competency needs. Path optimization takes students' career interests $Rs(t)$ and target competencies in the competency map as dual anchors. Combined with the multi-layer tuple data of the digital twin, it constructs a personalized initial learning path tailored to students' learning preferences and competency foundation through technologies such as reinforcement learning and graph traversal algorithms, clarifying the learning objectives, content modules and time planning of each stage, and realizing the precise docking of learning paths with competency maps.

As the learning process progresses, the digital twin updates students' competency data in real time and dynamically adjusts path nodes: when students' competency improvement speed exceeds expectations, it automatically adds high-level learning content and expands the knowledge boundary of the competency map; when students fall behind academically, it flexibly adjusts the learning rhythm and supplements connecting learning modules to ensure that the path always adapts to the evolving state of students' competencies. In addition, path optimization also links labor market demand data, dynamically adjusts the focus of competency cultivation combined with career interests $Rs(t)$, integrates interdisciplinary competencies required by the market into learning paths, realizes the forward-looking adaptation of learning paths to career development, and helps students build a competency system in line with market demand.

6.3. Practical Effectiveness Guarantee for Intervention and Path Optimization

Relying on the modular deployment architecture and standardized technical support, the operability, stability and scalability of learning intervention and path optimization are ensured. At the technical level, through standards such as Learning Tools Interoperability (LTI) and xAPI, the seamless connection between the digital twin and existing learning management systems and teaching tools is realized, ensuring the smooth implementation of intervention strategies and optimized paths. The data privacy security layer strictly protects the security of students' multi-dimensional data, providing reliable data support for intervention and path optimization.

At the practical level, the digital twin provides teachers with visual feedback of intervention and path optimization through the twin dashboard, helping teachers accurately grasp students' learning status and assist teachers in carrying out targeted teaching guidance, forming a collaborative mode of "digital twin autonomous intervention and teacher precise guidance". Meanwhile, the intervention and path optimization mechanism with competency maps as the core focuses on cultivating students' autonomous learning ability, guiding students to understand their own competency status in real time through the digital twin, independently adjust learning rhythm and direction, realize the transformation from "passively accepting intervention" to "actively autonomous learning", promote the construction of a personalized learning ecosystem, and ultimately achieve the precise adaptation of students' competencies to market demand and educational goals.

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