Construction and Practice of a Digital Production Line Teaching Reform System Driven by Four-Chain Integration

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Abstract. Aiming at the disconnection of the education chain, talent chain, industrial chain and innovation chain as well as the insufficient integration of emerging technologies in higher vocational education, this study proposes an innovative teaching reform system oriented to the industrial upgrading of new energy battery intelligent equipment in Guangdong. A systematic reform framework featured with four-chain integration driving and four-reality plus three-innovation supporting is constructed and implemented. This research establishes a closed-loop collaborative mechanism covering industrial demand orientation, educational agile response, talent quality support and innovative technology feedback. With digital twin and artificial intelligence technologies as core empowerment tools, the study reconstructs a 2+5+N modular curriculum system, builds a virtual-real integrated three-in-one training platform based on cloud computing, and adopts a four-stage progressive practical training path and project-driven teaching mode. Practical verification shows that the proposed reform system effectively narrows the skill gap between vocational college students and industrial post requirements. Students' comprehensive practical and innovative abilities are significantly improved, and the pre-job training cycle of graduates is shortened by more than 60%. The research results effectively solve the talent supply-demand mismatch problem in the intelligent manufacturing industry, and provide a replicable and promotable practical paradigm for the digital transformation of higher vocational education.

Keywords: Four-Chain Integration; Digital Production Line; Four Realities and Three Innovations; Industry-Education Integration; Vocational Education Digital Reform

1 Introduction

Against the backdrop of the "manufacturing-led" strategy in the Guangdong-Hong Kong-Macao Greater Bay Area and the transformation and upgrading of the new energy battery intelligent equipment industry in Guangdong, digital production lines have become the core engine driving high-quality regional economic development and the

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transformation of new productive forces [1]. However, the current higher vocational talent training system still faces the structural dilemma of disconnection among the education chain, talent chain, industrial chain, and innovation chain (the "four chains"), leading to a significant "generation gap" between students' skill reserves and the actual needs of the industry [2]. The core pain points lie in the lack of "four reality" practical elements (devoid of real products, real tasks, real processes, and real scenarios) and the lag in the integration of "three innovation" technologies (insufficient application of new technologies, new processes, and new specifications) [3]. This disconnection results in students lacking practical experience and prolonged pre-job training periods for graduates, severely restricting the digital transformation of the industry [4]. Addressing the above issues, this project, based on the national "Double High Plan", constructs a teaching reform system of "four-chain integration-driven and four-reality & three-innovation-supported" [5]. By establishing a closed-loop path of "demand proposed by the industrial chain, response from the education chain, support from the talent chain, and feedback from the innovation chain", this study aims to leverage the "three innovation" technologies to enhance the practical effectiveness of the "four realities", resolve the "two skins" problem in industry-education integration, and provide a replicable model reference for the digital transformation of vocational education [6].

2 Logical Architecture of the Four-Chain Integration-Driven Teaching Reform System

In the context of in-depth digital transformation, the teaching reform of digital production lines is not a simple superposition of teaching links but a systematic reconstruction based on the deep coupling of the "four chains" [7]. This system adopts a top-level design of "industrial chain demand-oriented, education chain response-centered, talent chain support-targeted, and innovation chain empowerment-driven", aiming to build a collaboratively evolving closed-loop logical architecture. The specific logical relationships are shown in Figure 1.

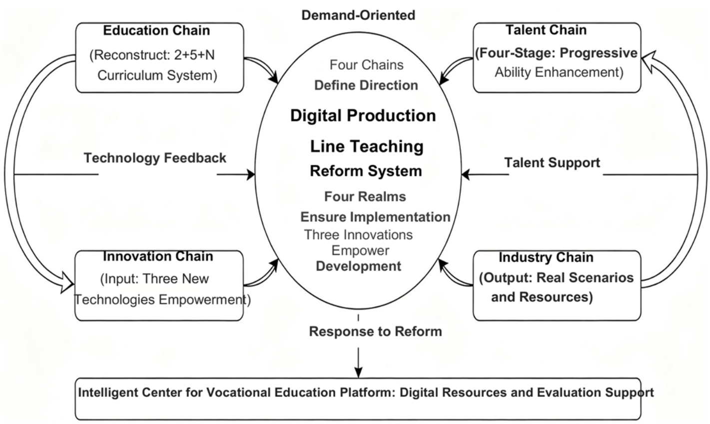

Fig. 1. Logical Architecture Diagram of the "Four-Chain Integration" Teaching Reform System

2.1 Driving Layer: Closed-Loop Operation Logic of Four-Chain Connection

The logical starting point of the system is rooted in the dynamic demands of the industrial chain. The industrial chain clarifies the specific indicators of talent specifications for the education chain by outputting real products, real tasks, and real scenarios. In response, the education chain conducts agile responses by reconstructing the "2+5+N" modular curriculum system and training environment, ensuring that talent training keeps pace with industrial evolution [8]. The talent chain follows a four-stage progressive path of "vocational cognition—basic skills—core skills—innovation and optimization" to provide high-quality technical and skilled support for industrial upgrading. Meanwhile, the innovation chain transforms cutting-edge technologies such as digital twins and AI into high-quality teaching resources and dynamically injects them into the educational process, achieving synchronous resonance between technological iteration and talent training.

2.2 Support Layer: Concrete Implementation of Four Realities and Three Innovations

The effective operation of the logical architecture relies on the concrete implementation of the "four realities and three innovations" support system. In terms of "four realities" implementation [9], the system transforms real products (e.g., battery cells), real tasks (e.g., production line optimization), real processes (e.g., cell synthesis), and real scenarios (e.g., equipment failures) from the industrial chain into core teaching carriers [9]. Through jointly built new energy battery production lines between schools and enterprises, students can practice in an environment highly consistent with actual enterprise production, effectively solving the chronic problems of false training scenarios and disconnection from actual production in traditional teaching [10]. In terms of "three innovation" empowerment, the innovation chain dynamically integrates new technologies such as digital twins, AI fault early warning, new energy lamination processes, and new industrial internet specifications into the entire teaching process [11]. This not only eliminates the "generation gap" between students' skills and industrial needs but also endows students with innovative literacy to solve complex engineering problems [12].

2.3 Platform Layer: Virtual-Real Linkage and Cloud Collaboration

Through the collaborative operation of the ICVE (Intelligent Vocational Education) and the "four-reality virtual line & four-reality physical line". As the "digital nerve center" of the digital production line teaching reform system, this platform serves as the core carrier connecting the education chain, talent chain, industrial chain, and innovation chain [13]. In terms of operation mechanism, the virtual line focuses on new technology rehearsal, process simulation, and low-cost trial-and-error; the physical line undertakes real skill application, production verification, and practical training. The two achieve deep virtual-real linkage through data synchronization. The ICVE fully integrates the digital resources of the "four chains" and uses the "ICVE AI-Enhanced

Courses" to collect real-time behavioral data of students performing "four reality" tasks, portraying accurate digital portraits of practical skills and implementing whole-process evaluation. The "AI Enhanced Course" assistant utilizes the Vocational Education Large Model (Vocational LLM) and Transformer-based sequential learning technology to process students' learning behavior data, serving as a "digital nerve center" to achieve deep "four-chain" integration. The system's training is based on a multi-modal case library covering the entire battery production process, featuring a total of over 138 course resources; it accurately extracts student behavioral characteristics by deeply mining more than 1.67 million accumulated log data entries. Regarding the tracking mechanism, the system monitors learning participation in video content, classroom activity levels, and assignment completion and quality, thereby sketching precise digital portraits of practical skills and implementing whole-process evaluation. This data-driven closed-loop of personalized tutoring and evaluation effectively resolves the subjective dilemmas inherent in traditional evaluation methods. This cloud collaboration mechanism ensures that the teaching system can conduct agile iteration and dynamic adjustment based on feedback data, maximizing educational effectiveness [14].

3 Reconstruction of the Modular Curriculum System for Digital Production Lines

Against the backdrop of the rapid iteration of the new energy battery intelligent equipment industry, the core of the teaching reform for digital production lines lies in breaking the knowledge barriers of traditional discipline-oriented education and building a curriculum system that can agilely respond to industrial technological changes. Starting from the industrial chain post competency map, this system forms a "2+5+N" modular architecture of "2 platforms + 5 modules + N practice packages", achieving the precise mapping between the content of the education chain and the needs of the industrial chain.

3.1 Design of the "2+5+N" Modular Curriculum Architecture

The top-level design of the system is supported by a general education platform and a professional foundation platform, aiming to consolidate students' basic professional literacy and interdisciplinary general skills. The core teaching layer focuses on five professional modules: intelligent control, industrial network integration, industrial robot integration, intelligent equipment integration, and mechanical design and manufacturing [15]. In this architecture, digital twin technology is positioned as the "virtual mirror" of the intelligent manufacturing technology cluster, systematically integrated with intelligent control (responsible for the "execution terminal") and industrial networks (responsible for the "neural network"), jointly constructing the "digital nervous system" of the production line. In addition, "N" enterprise practical skill packages (e.g., new energy battery cell production line process packages) are developed through in-depth school-enterprise collaboration, transforming real production line assembly, adjustment, and maintenance projects from leading enterprises such as Inovance Technology and New Energy Technology into teaching units, ensuring that teaching content keeps pace with frontline industrial technologies. The specific curriculum architecture and training path are shown in Figure 2.

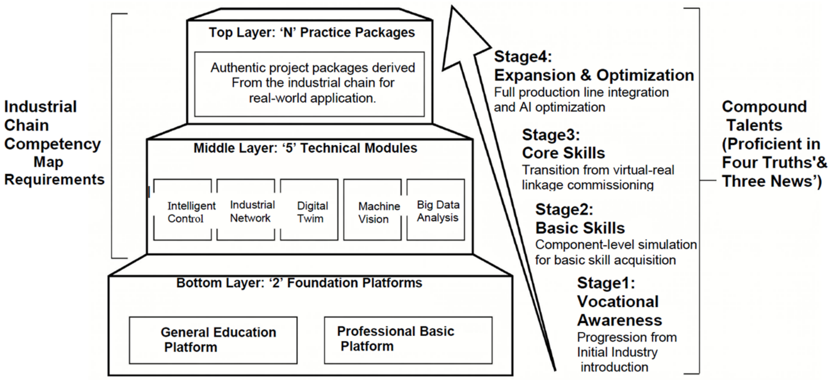

Fig. 2. The "2+5+N' Modular Curriculum & 'Four-Stage Progressive' Training System.

3.2 Four-Stage Progressive Practical Teaching Path

To follow the growth pattern of technical and skilled talents, the system establishes a four-stage progressive training path of "vocational cognition—basic skill consolidation—core skill strengthening—skill expansion and optimization". In the vocational cognition stage, courses such as Introduction to New Energy Battery Intelligent Equipment introduce real enterprise cases such as CATL's "digital twin + AI", enabling students to form a perceptual understanding of the intelligent manufacturing industry. Subsequently, entering the basic skill stage, students rely on digital twin technology to conduct NX MCD basic design and PLC logic verification for "four reality" components such as feeding mechanisms and control panels, mastering component-level simulation skills. In the core skill stage, teaching content delves into complex tasks such as automated production line joint debugging and industrial internet data collection. Through 1:1 data synchronization between the "four-reality virtual line" and the "four-reality physical line", virtual-real linkage debugging is realized. Finally, in the expansion and optimization stage, students participate in real industrial chain technical improvement projects, such as designing AI-based production line OEE (Overall Equipment Effectiveness) improvement schemes, realizing the sublimation of innovation capabilities through the comprehensive application of new technologies, new processes, and new specifications.

3.3 Dynamic Adaptation Update Mechanism and Resource Support

The system introduces an "industry-agile driven" development mechanism, effectively solving the pain point that curriculum revision lags behind technological iteration. By establishing a dynamic adjustment center composed of senior enterprise engineers, scientific research experts, and teaching masters, cutting-edge elements such as digital twin simulation, AI fault early warning, and new energy lamination processes are injected into the teaching syllabus in real time. Meanwhile, relying on the "ICVE" of Guangdong Polytechnic of Industry and Commerce, a digital case resource library with a total volume of more than 1TB has been built through school-enterprise-research collaboration. Through the interactive collaboration of loose-leaf textbooks and cloud-based AI course agents (e.g., the Digital Twin Technology Application agent), a virtual-real linked, multi-dimensional interactive learning environment is created for students, ensuring that talent training specifications are highly adapted to the needs of new productive forces in the industry.

4 Construction of the "Three-In-One" Teaching Environment and Resource Support Platform

The deepening of the teaching reform for digital production lines inevitably requires the deep integration of physical and virtual spaces to support the collaborative operation of "four-chain" resources. Breaking the limitation of single-function traditional training rooms, this system constructs a virtual-real linked, cloud-empowered "three-in-one" teaching environment by integrating the "four-reality virtual line, four-reality physical line, and ICVE ". The so-called "three-in-one" refers to the deep coupling of a virtual simulation space for new technology rehearsal, a physical production space for real skill application, and a cloud resource space for digital governance, forming a systematically integrated training carrier with complementary functions and intercommunicating data. This environment not only provides a material foundation for the concrete implementation of "four reality" elements but also serves as the core platform for transforming "three innovation" technologies into educational driving forces, realizing the systematic reconstruction of teaching spaces and industrial scenarios.

4.1 Construction of a Virtual-Real Coupled Productive Training Base

Based on the real needs of the new energy battery intelligent equipment industry chain in Guangdong Province, this system, in collaboration with leading enterprises such as Inovance Technology and New Energy Technology, replicates a highly simulated production operation environment on campus. The four-reality physical line is equipped with mainstream industrial equipment such as industrial robots and vision systems, truly restoring the entire process of cell synthesis. At the same time, schools and enterprises develop a supporting four-reality virtual line at a 1:1 ratio, digitally modeling complex scenarios such as lamination processes and equipment failures relying on digital twin technology. This virtual-real coupled architecture provides students with space for low-cost trial-and-error and new technology rehearsal. Before operating on the physical line, students must complete process simulation and program verification in the virtual space, ensuring the scientificity and safety of the training process through the approach of "practicing real skills via virtual simulation and integrating virtuality with reality".

4.2 Digital Nerve Center Function of the ICVE (Intelligent Vocational Education)

As the "digital nerve center" of the entire teaching system, which realizes the digital governance of the teaching process by integrating various resources of the education chain, industrial chain, talent chain, and innovation chain [16]. The platform stores a digital textbook and case resource library of more than 1TB developed through school-enterprise collaboration, and integrates vocational education large models to build AI course agents such as Digital Twin Technology Application. In teaching implementation, the platform's "ICVE AI-Enhanced Courses" can collect multi-source heterogeneous data in real time when students perform "four reality" tasks, and outline accurate digital portraits of practical skills through background algorithm analysis. This big data-based whole-process evaluation mechanism changes the traditional result-oriented assessment method, providing a scientific basis for teachers to carry out targeted tutoring and students' personalized growth.

4.3 Dynamic Resource Update and Closed-Loop Operation Mechanism

The efficient operation of the "three-in-one" environment benefits from a sound dynamic resource update and closed-loop operation mechanism. By establishing a committee composed of university professors, enterprise technical directors, and scientific research experts, the system adheres to the logic of "demand proposed by the industrial chain, solutions proposed by the innovation chain, teaching implemented by the education chain, and support provided by the talent chain". Every year, in response to industrial technological changes, the platform dynamically updates the real product model library and real task case library, and timely injects "three innovation" elements such as AI fault early warning and industrial internet standards into the virtual simulation module. This cloud collaboration mechanism ensures that teaching and training resources always keep pace with the industrial frontiers, transforming the training environment from a simple hardware stack into a self-evolving, continuously empowering innovative talent cultivation ecosystem [17].

5 "Four-Chain Collaboration + Four-Reality Project" Teaching Practice Model

The ultimate goal of the teaching reform for digital production lines lies in the implementation of the teaching process. This system innovatively implements the "four-chain collaboration + four-reality project" model, starting from the real needs of the industrial chain, realizing high-quality output of the talent chain through innovation chain technology empowerment and education chain curriculum bearing, forming a closed-loop practical path of "demand introduction—technology rehearsal—practical implementation".

5.1 Industrial Chain Demand-Oriented Project Design Mechanism

Teaching practice starts with the accurate capture of real pain points in the industrial chain. Relying on the school-enterprise-research collaboration mechanism, the system establishes a project design model of "demand proposed by the industrial chain and jointly transformed by schools and enterprises". The project team conducts in-depth visits to enterprise production lines, transforming real tasks such as "new energy battery production line beat optimization" into teaching project packages containing real engineering backgrounds, technical parameters, and assessment standards [18]. This mechanism ensures the high adaptation of teaching content to industrial needs, changing the status quo that training projects were previously divorced from actual production, enabling students to contact the industry's most cutting-edge process requirements and technical challenges while in school.

5.2 "Four Realities and Three Innovations" Integrated Project Implementation Process

In specific implementation, the system implements a five-step cyclic process consisting of "real scenario introduction—real task decomposition—three-innovation rehearsal—real equipment implementation—new specification assessment". First, the digital twin model of real industrial production scenarios is introduced through the ICVE to guide students to form a perceptual understanding; then, complex tasks are decomposed into operable learning units. On this basis, students use digital twin and AI technologies to conduct low-cost process rehearsal and scheme verification on the virtual line. After successful rehearsal, students implement the scheme on the physical line using real equipment. Finally, assessments are conducted in accordance with the latest industry specifications. This process realizes "practicing real skills via virtual simulation and integrating virtuality with reality", significantly improving students' ability to solve complex engineering problems.

5.3 Digital Evaluation-Driven Closed-Loop Improvement System

To ensure the continuous evolution of the model, the system constructs a digital evaluation and feedback mechanism based on the ICVE. During project implementation, the platform collects real-time behavioral data such as students' operation trajectories, response times, and fault handling logic. Through in-depth analysis by the vocational education large model, the platform can outline accurate digital portraits of practical skills for each student. This portrait not only serves as a reference for summative evaluation but also provides real-time feedback to teachers for dynamically adjusting teaching strategies, and serves as a basis for industrial chain enterprises to select talents. Meanwhile, the committee regularly updates the project library based on evaluation data and industrial iteration, continuously injecting new processes and specifications into teaching, ensuring that the practical model is in a virtuous state of spiral ascent.

6 Construction of a Multi-Dimensional Intelligent Teaching Evaluation System

Relying on the ICVE and the "ICVE AI-Enhanced Courses", the teaching reform for digital production lines constructs a school-enterprise dual-subject, whole-process intelligent evaluation framework. Taking industrial chain post standards as the benchmark, it leverages big data collection and vocational education large model analysis to achieve accurate characterization of talent training quality. Breaking the limitation of single-school evaluation, the system establishes a feedback mechanism for in-depth interaction between the education chain and industrial chain. Enterprise tutors focus on assessing the execution quality of "four reality" tasks and post competency, while university teachers are responsible for evaluating professional theories and professional ethics. The dynamic allocation of evaluation weights ensures that talent supply keeps pace with industry standards. In terms of implementation paths, the system promotes the deep integration of "teaching, learning, practice, and evaluation" through digital technology. During students' execution of "four reality" tasks, the platform collects real-time behavioral data and generates "digital portraits" of practical skills, providing a basis for personalized learning assistance and significantly shortening the pre-job training period. Meanwhile, the evaluation system is closely aligned with the talent chain's "four-stage progressive" path, implementing staged assessments from perceptual evaluation to virtual-real linkage debugging assessment and then to innovative scheme evaluation, realizing the deep connection between curriculum evaluation and vocational skill level certification.

As shown in Table 1, the table systematically sorts out the four core dimensions of the evaluation system, and details the corresponding "four realities and three innovations" elements, evaluation subjects, and intelligent data collection sources for each dimension, providing quantitative support for dynamic monitoring and accurate feedback of teaching quality. The multi-dimensional intelligent teaching evaluation scale was validated with an inter-rater reliability (Cronbach's α) of 0.89. Weights are dynamically assigned across four subjects: University Teachers (30%) for ethics and theory, Enterprise Tutors (40%) for task execution quality, Innovation Chain Experts (20%) for new technology application, and the Joint Committee (10%) for overall chain coordination. Rater disagreement is resolved via a weighted consensus algorithm that cross-references the objective behavioral data recorded by the ICVE AI-Enhanced Courses.

Table 1. Multi-Dimensional Intelligent Teaching Evaluation Scale for Digital Production Lines (Four-Chain Collaboration + Four Realities and Three Innovations).

Evaluation Dimension	Core Evaluation Indicators (Corresponding to "Four Realities and Three Innovations" Elements)	Evaluation Subject	Intelligent Assessment Tools and Data Sources
Professional Ethics Evaluation	Implementation of industrial safety standards, teamwork ability, professional ethics performance	Teachers, Enterprise Tutors	Behavioral trajectories, attendance and log data recorded by ICVE (Intelligent Vocational Education)

New Technology Application Evaluation	Digital twin modeling accuracy, AI fault early warning accuracy, 5G communication configuration	Teachers, Innovation Chain Experts	Program codes and verification reports exported from the virtual simulation platform
Four Reality Task Quality Evaluation	Battery cell synthesis process compliance rate, production line OEE improvement ratio, fault resolution rate	Enterprise Tutors, Intelligent System	Physical line practical operation data, real-time dashboards of production management systems
Four-Chain Collaboration Effect Evaluation	Post adaptability, 1+X certificate acquisition rate, pre-job training period reduction rate	School-Enterprise Joint Committee	Accurate portraits from ICVE (Intelligent Vocational Education), graduate employment tracking data platform
Innovation and Improvement Ability Evaluation	Production line optimization schemes based on three-innovation technologies, complex engineering problem-solving ability	Innovation Chain Institution Experts	Innovation project package acceptance reports, patent/achievement libraries

7 Analysis of Practical Effects

The implementation of the four-chain integration-driven teaching reform system for digital production lines has systematically solved the long-standing mismatch between talent supply and demand in higher vocational education. Through the deep coupling of "four realities and three innovations" elements, this project has achieved remarkable results in improving students' practical capabilities, driving high-quality employment, and reconstructing the digital teaching ecosystem, forming a reform model with demonstration significance for vocational education.

7.1 Leapfrog Improvement in Students' Professional Practical Capabilities and Innovative Literacy

Relying on the "2+5+N" modular curriculum system and the four-stage progressive training path, students' competency in solving complex engineering problems has been significantly enhanced. Empirical data shows that the average scores of students in pilot classes in core skill modules such as PLC programming, system virtual-real linkage debugging, and automated fault troubleshooting have increased by about 25% compared with previous cohorts. A comparative analysis was conducted between the pilot class ($n=45$) and a control class ($n=45$) from the previous cohort. The evaluation focused on core skill modules using a standardized 100-point scale. The pilot class achieved a mean score of 88.5 ($SD=5.2$) in PLC programming and system debugging, while the control class mean was 70.8 ($SD=7.4$). An independent samples t-test indicated a significant difference between the two groups ($t=13.2$, $p < 0.01$), validating the substantial impact of the "Four-Reality" project-driven mode on student performance.

In the hierarchical assessment of the talent chain, students exhibit high post adaptability, with a stable acquisition rate of over 90% for "1+X" vocational skill level certificates. In addition, technological empowerment from the innovation chain has stimulated students' innovation and entrepreneurship vitality. The project team has won gold and silver awards in national intelligent automation innovation competitions such as the "Inovance Cup" and relevant provincial skill competitions for consecutive years, ranking among the top in the industry.

7.2 High-Quality Employment and Industrial Feedback Driven by In-Depth Industry-Education Adaptation

Establishing a closed-loop path oriented by industrial chain demand, this system effectively solves the "two skins" dilemma of talent supply and demand. Benefiting from systematic training in "four reality" scenarios, the industry chain counterpart employment rate of graduates reaches 85%, and the pre-job training period after employment is shortened by more than 60% compared with the traditional training model, greatly reducing enterprises' employment costs. From the market feedback of the talent chain, the average starting salary of graduates is 20% higher than the national average of similar majors, and the satisfaction of leading industrial chain enterprises with talent training quality has increased to more than 85%. Meanwhile, the jointly built industrial digital innovation center between schools and enterprises has approved more than 50 vertical and horizontal research projects, with cumulative transformation of scientific research achievements and technical service economic benefits reaching 20 million yuan, The 20 million yuan economic benefit is disaggregated into:2 million yuan from vertical government research grants (provincial and national levels) and 18 million yuan from horizontal technology service contracts, including production line beat optimization and AI defect detection services provided to industry leaders like Inovance and New Energy Technology. Outcomes are co-owned by the school-enterprise innovation center, with a royalty-sharing mechanism that reinvests 60% of technical service income into curriculum resource iteration. realizing strong support and innovative feedback from the education chain to the industrial chain.

7.3 Construction of a New Digital Teaching Ecosystem and Demonstration and Leading Effects

Relying on the ICVE (Intelligent Vocational Education) and the "three-in-one" training environment, the project has successfully reshaped the digital teaching space. At present, the school-enterprise-research collaboratively developed "four realities and three innovations" digital case resource library has exceeded 1TB in total volume, covering the entire production process of new energy batteries. As the "digital nerve center", the ICVE (Intelligent Vocational Education) has served more than 3,000 students cumulatively, and its "ICVE AI-Enhanced Courses" has realized personalized learning assistance and accurate digital portrait evaluation. The "industry-agile driven" textbook development mechanism formed by the system has been promoted in the national "Robot +" industry-education integration community, with cumulative authorized patents and software copyrights exceeding 50 pieces. The 50+ authorized intellectual property outputs include 15 invention patents related to digital twin synchronization algorithms, 20 utility model patents for "Four-Reality" hardware modules, and 18 software copyrights. These achievements not only promote the intelligent upgrading of professional groups but also provide a highly valuable practical model for the digital transformation of vocational education in China.

8 Conclusion

Based on the background of industrial upgrading in the Greater Bay Area, this project constructs a digital production line teaching reform system characterized by "four-chain integration and four realities & three innovations". Relying on the "2+5+N" modular curriculum and the virtual-real linked intelligent training environment, it implements four-stage progressive training, effectively solving the problem of industry-education disconnection. The results show that students' practical capabilities are significantly improved, and the pre-job training period for graduates is shortened by more than 60%, achieving precise adaptation between talent supply and industrial demand, and providing a replicable practical model for the digital transformation of vocational education.

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