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Connotation and Characteristics of Artificial Intelligence-Enabled Technology and Engineering Project-Based Learning

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Abstract: Intelligent technologies represented by AI are profoundly transforming engineering practice. The General High School Technology and Engineering Curriculum Standards (2017 Edition, 2025 Revision) mandates cultivating students' ability to solve complex problems in real technical contexts, while traditional PBL faces issues like insufficient situational authenticity and inadequate process support. This study focuses on the "AI-enabled Technology and Engineering Project-Based Learning (AI-T&E PBL)" paradigm, defining its theoretical connotation through three dimensions: human-machine collaborative literacy development, core ideologies (Intelligent Enhancement, Precision Adaptation, Generative Co-Creation), and the coupling of objectives, processes, and technologies. Compared with traditional PBL, the study identifies core differences and five key characteristics (e.g., dynamic contexts, intelligent adaptive scaffolding). Practical suggestions cover project design, technical environment, teacher development, and evaluation. The paradigm reshapes technology and engineering education, supporting the cultivation of future engineering innovators.

Keywords: AI-enabled; Technology and Engineering Project-Based Learning; Human-Machine Collaboration; Core Literacy; Teaching Paradigm

1. Introduction

Currently, intelligent technologies represented by artificial intelligence (AI) are profoundly transforming the form of engineering practice, posing higher requirements for technology and engineering education. The General High School Technology and Engineering Curriculum Standards (2017 Edition, 2025 Revision) clearly state that students should be cultivated to solve complex problems in real technical contexts. However, traditional project-based learning (PBL) faces practical dilemmas such as insufficient situational authenticity, lack of process support, and difficulties in literacy assessment when achieving this goal[1].

To respond to the requirements of the curriculum standards and address the challenges of traditional models, this study focuses on the emerging paradigm of "Artificial Intelligence-Enabled Technology and Engineering Project-Based Learning (AI-T&E PBL)", aiming to systematically analyze its theoretical connotation and practical characteristics. Starting from the new paradigm of human-machine collaborative literacy development, this research reveals the transformative role of intelligent technologies in learning objectives, processes, and evaluation through comparative analysis with traditional models. It extracts the core characteristics of this paradigm in situational creation, process support, and evaluation methods, providing theoretical references and practical paths for the innovative development of technology and engineering education in the intelligent era.

2. Theoretical connotation of AI-Enabled technology and engineering project-based learning

To deeply grasp the enabling effect of AI on technology and engineering project-based learning, it is necessary to go beyond the superficial understanding of tool application and conduct systematic theoretical construction from three dimensions: conceptual essence, ideological pillars, and system composition. This is not only the logical starting point for understanding this new educational practice form but also the fundamental basis for distinguishing it from traditional models.

2.1. Conceptual definition: a new paradigm of human-machine collaborative literacy development

Technology and engineering courses mainly adopt PBL as their implementation form. The core is to enable students to develop core literacies such as technical awareness, engineering thinking, innovative design, graphical expression, and materialization ability through practical processes including design, production, experimentation, and optimization in real problem contexts. The integration of AI is not a simple addition of technical tools but promotes the evolution of this learning paradigm into a new model of human-machine collaborative literacy development.

In this paradigm, AI acts as a cognitive collaborator, process supporter, and resource allocator, forming an intelligent learning ecosystem together with students and teachers. It drives the transformation of learning from "teacher-led and student-executed" to "data-driven and human-machine co-cultivated"[2]. The core goal of AI-T&E PBL is to support students to participate more deeply in engineering practice, develop higher-order thinking more systematically, and achieve personalized literacy growth through intelligent technologies in complex, open, and dynamic engineering projects.

2.2. Core ideologies: three pillars of intelligence, adaptation, and co-creation

This new paradigm is supported by three core ideologies, which jointly define its value orientation and action logic, providing fundamental guidelines for the implementation of the paradigm.

Firstly, the Intelligent Enhancement Concept. This ideology advocates that AI should serve as a "cognitive partner" with the core goal of enhancing rather than replacing human intelligence[3]. In PBL, AI can process massive data, run complex models, and conduct high-speed simulations, helping students explore complex problem spaces beyond individual experience and computational capabilities—such as simulating the performance of different materials in extreme environments or predicting the long-term chain effects of urban transportation systems. This allows students to concentrate their limited cognitive resources on higher-order tasks: accurately defining problems, balancing multiple values, making ethical judgments, and conducting comprehensive innovations. Thus, AI becomes a "multiplier" for students' thinking and abilities, assisting teachers and students in addressing unprecedented engineering challenges.

Secondly, the Precision Adaptation Concept. This ideology aims to resolve the contradiction between "unified teaching" and "individualized needs" in traditional PBL. By continuously collecting and analyzing multimodal data generated by students during the project—including dialogue texts, iterative sequences of design sketches, operational behavior logs, and even emotional state signals—AI can construct refined learner profiles, diagnosing their cognitive obstacles, skill weaknesses, and interest triggers in near real-time. Based on this, the learning system can dynamically adjust task difficulty, push customized learning resources, and provide appropriate prompts and scaffolding, realizing "one student, one pathway" personalized learning support. This makes "teaching students in accordance with their aptitude" possible in large-scale education, ensuring that each student receives effective challenges and growth support within their "zone of proximal development".

Thirdly, the Generative Co-Creation Concept. This ideology emphasizes that learning is a dynamic interactive process in which humans and AI jointly create knowledge, solutions, and meanings. Learning outcomes are not reproductions of pre-set knowledge but are generated through continuous human-machine dialogue and collaboration. For example, generative AI can assist students in brainstorming, inspiring novel problem perspectives and initial solution prototypes; simulation environments based on physical engines can interact with students' design decisions in real-time, jointly "calculating" the feasibility and potential flaws of solutions to drive iterative optimization. In this process, AI is not only an information source but also a thinking collaborator, creativity inspirer, and witness of iteration. The final project outcomes are the product of in-depth interweaving and collaborative evolution of human and machine intelligence.

2.3. Constituent dimensions: systematic coupling of objectives, processes, and technologies

AI-T&E PBL is a complex educational system closely coupled by three dimensions: objectives, processes, and technologies. The internal consistency of these three ensures the effective implementation of the paradigm's ideologies.

In the objective dimension, the system always takes the development of students' integrated core literacies in technology and engineering as its fundamental orientation. The design and evaluation of all learning activities are anchored in the cultivation of technical awareness (understanding the relationship between technology, society, and the environment), engineering thinking (systematic analysis and trade-off optimization), innovative design (creatively solving problems), graphical expression (visual communication), and materialization ability (transforming ideas into entities). The enabling role of AI lies in deepening the construction process of these literacies by creating rich contexts, providing analytical tools, and expanding creative possibilities.

In the process dimension, it forms a closed-loop and progressive intelligent learning process driven by data flow: first, "intelligent situational perception", where students enter highly immersive and challenging real problem scenarios generated or enhanced by AI; then, "data-driven inquiry", where students use AI tools to collect, process, and analyze information to form and verify hypotheses; next, the core stage of "collaborative design iteration", where humans and machines collaborate on scheme conception, modeling, simulation testing, and continuous optimization, with AI providing real-time feedback and alternative solution suggestions; finally, "intelligent evaluation and reflection", where the system provides comprehensive evaluation reports based on the analysis of multimodal data throughout the process, guiding students to conduct metacognitive reflection and laying the foundation for new learning cycles. This process is highly interactive, iteratively generative, and evidence-centered.

In the technical dimension, its implementation relies on the integrated support of collaborative key technology clusters: generative AI is responsible for content generation, natural language dialogue, and creative assistance; learning analytics technology is used for mining, modeling, and visualizing data on learning behaviors, processes, and outcomes; simulation and digital twin technologies construct high-fidelity, operable virtual practice environments to support low-cost trial and error; sensing and computer vision technologies capture physical operations, work status, and environmental parameters. These technologies are not simply stacked but organically linked under a unified educational design framework, forming a complete technical ecosystem supporting intelligent perception, analysis, interaction, and creation, which collectively serves the literacy-oriented deep learning experience.

3. From traditional to intelligent: paradigm evolution and core differences

Traditional Technology and Engineering Project-Based Learning (T&E PBL) has laid a foundation for cultivating students' practical abilities and engineering thinking. Its model usually manifests as: in pre-designed, relatively clearly structured real or simulated contexts by teachers, students work in groups to go through relatively linear processes such as problem discovery, scheme design, prototype production, and testing optimization, and finally present learning outcomes in the form of physical works or reports. However, this paradigm faces significant challenges in the complexity and dynamics of contexts, precise support and personalized adaptation of processes, and the comprehensiveness and developmental nature of evaluation.

The in-depth integration of AI is not a simple technical upgrade of the traditional model but drives the fundamental evolution of T&E PBL from an "experience-driven and group-promoted" paradigm to a "data-driven and human-machine collaborative" new paradigm. The core differences between the two can be systematically presented through the following dimensions:

Table 1. Comparison between traditional T&E PBL and AI-T&E PBL

Comparison Dimensions	Traditional T&E PBL Paradigm	AI-Enabled T&E PBL (AI-T&E PBL) Paradigm
Goal Orientation	Unified mastery: Focuses on the achievement of common knowledge and skill objectives, emphasizing the standardized completion of works	Personalized literacy development: On the basis of common objectives, relying on dynamic learning data to support students' differentiated advancement and strength development in core literacies such as technical awareness and engineering thinking
Situations and Problems	Pre-designed and static: Problem contexts are usually pre-designed by teachers, relatively fixed during the project cycle, and their complexity and openness are limited by teachers' experience and classroom conditions	Generative and dynamic: AI can generate or dynamically adjust problem contexts based on real-time data (such as social hot topics, technological frontiers, and campus data), and construct high-fidelity, interactive virtual simulation environments (such as digital twin factories). It supports students to explore complex, high-risk, or macro engineering problems that are inaccessible in traditional classrooms[4]
Learning Process	Linear and closed: Clear division of process stages, single path, limited opportunities for iterative optimization, and substantive testing usually conducted after prototype production	Iterative and open: AI supports a rapid micro-iteration cycle of "design-simulation-test". Students can predict performance and identify potential conflicts through simulation during the scheme conception stage, turning the learning process into a spiral-up, non-linear exploration process, which greatly strengthens systematic thinking and optimization capabilities
Guidance and Support	Teacher-centered and unified guidance: Teachers are the core knowledge sources and decision-makers; guidance is difficult to cover the personalized processes of all groups, and feedback is delayed	Human-machine collaborative and adaptive support: AI acts as an intelligent tutor (AI Tutor), providing 24/7 personalized scaffolding. For example, it automatically identifies structural risks in design drawings, recommends optimization algorithms, warns of experimental safety hazards, and dynamically pushes learning resources matching students' current "zone of proximal development". It frees teachers from repetitive guidance, allowing them to focus more on stimulating higher-order thinking and guiding humanistic ethics
Evaluation and Reflection	Outcome-oriented and summative-dominated: Evaluation focuses on final works and reports; process evaluation relies on teachers' limited observations, making it difficult to quantitatively record thinking processes	Whole-process, data-driven, and developmental: AI can unobtrusively collect whole-process multimodal data (such as iterative versions of sketches, collaborative dialogues, operation logs, and simulation experimental data). Through analysis, it visualizes students' ability maps, thinking trajectories, and collaborative networks. Evaluation not only focuses on outcomes but also deeply reveals the process of literacy formation, providing evidence support for personalized reflection and precise teaching intervention

The core essence of paradigm evolution is that AI-T&E PBL transforms learning from a deterministic process mainly designed and managed by human teachers into a more generative and exploratory complex adaptive system jointly driven by human wisdom and machine intelligence. In this system, students are not only users of technology but also problem solvers and knowledge creators collaborating with intelligent agents. This paradigm goes beyond tool assistance, reshaping the objectives, paths, relationships, and ecology of learning. It enables technology and engineering education to more effectively respond to the uncertainty of the real world and cultivate future innovators capable of mastering intelligent technologies to solve complex engineering problems.

4. Core characteristics of AI-Enabled technology and engineering project-based learning

Based on the paradigm evolution from traditional to intelligent, AI-T&E PBL presents a distinct and iconic characteristic system with technical and engineering disciplinary attributes. These characteristics are not modifications to the traditional model but structural innovations driven by the deep integration of intelligent technologies into the core of engineering and technology education. They collectively shape a new form of intelligent learning with technical literacy, engineering thinking, innovative design, graphical expression, and materialization ability as the core.

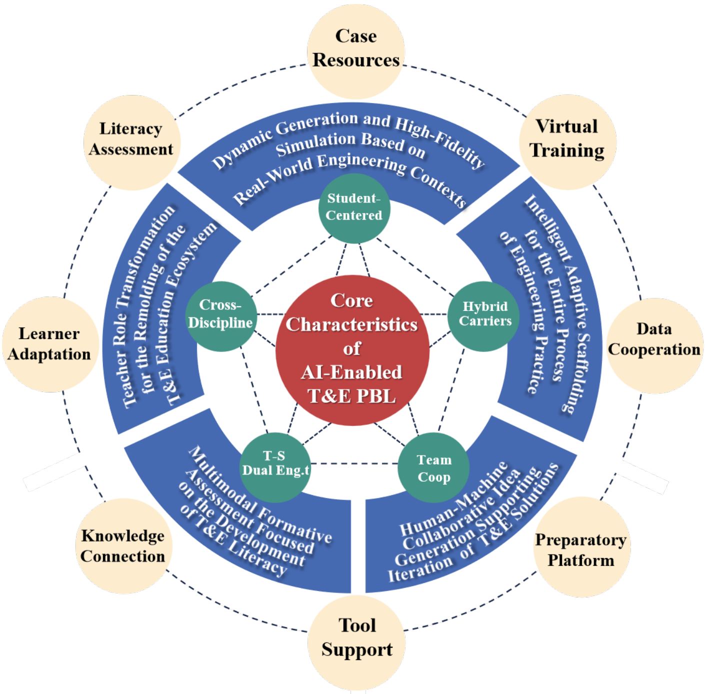

Figure 1. Core characteristics of artificial intelligence-enabled technology and engineering project-based learning

4.1. Characteristic 1: dynamic generation and high-fidelity simulation based on real engineering contexts

Traditional PBL has strong pre-designed situations, often presented in simplified models. The core characteristic of AI-T&E PBL lies in the use of cutting-edge technologies such as digital twins and multi-agent simulation to construct dynamically generative and high-fidelity contexts that deeply integrate technical parameters, engineering constraints, and system complexity. Such contexts are not static scenes but “living systems” that can respond in real time to students’ design decisions, integrate real engineering variables (such as material properties, environmental disturbances, cost constraints, and safety standards), and continuously evolve.

For example, in the “automated palletizing system” project, AI can generate a high-fidelity virtual simulation environment based on industrial palletizing scenario parameters and material property data. Every adjustment of module functions by students (such as optimization of grasping logic, setting of stacking modes, and configuration of signal interfaces) will immediately trigger chain changes in system operation efficiency, stacking stability, and fault response speed[5]. This immersive and multi-variable linked technical context requires students to conduct systematic analysis and trade-off decisions under multiple constraints such as performance, safety, cost, and sustainability, just like engineers. It goes beyond general “problem-solving”, exposing students to the inherent uncertainty, multi-objective optimization, and long-cycle effects in engineering technology, thereby deeply tempering their core engineering literacies of systematic thinking, risk assessment, and technical responsibility. Here, AI not only provides a “safe sandbox” for trial and error but also acts as a “perspective lens” to reveal the inherent laws of complex technical systems.

4.2. Characteristic 2: intelligent adaptive scaffolding for the entire process of engineering practice

Traditional support relies on teachers’ experience, making it difficult to cover the personalized engineering practice difficulties of all students. The core of this characteristic is to construct an intelligent adaptive scaffolding that accompanies the entire cycle of engineering and technical practice, with deep perception and precise intervention capabilities[6]. By analyzing multimodal data in real time generated by students in the entire chain of “design-modeling-material selection-processing-testing-optimization” (such as 3D modeling history, circuit simulation parameters, processing technology selection, sensor data streams, and debugging logs), it can accurately locate their technical thinking gaps or practical skill bottlenecks. At the “teaching moment” when intervention is most needed, it provides customized resources, prompts, or simplified tasks[7].

For example, when students encounter difficulties in constructing the control logic of the “automatic irrigation system”, the system can automatically push code modules of similar open-source projects as references, or compare their current flowcharts with common error patterns and highlight potential logical vulnerabilities. This support is context-aware, diagnostic-preventive, and personalized guiding. It partially transforms teachers’ roles from “omnipotent problem solvers” to “higher-order guides”, while AI undertakes basic and repetitive technical tutoring. It realizes full-cycle, refined, and data-driven accompanying support for each student’s engineering and technical practice process, effectively promoting the substantial development of materialization ability and engineering thinking.

4.3. Characteristic 3: human-machine collaborative idea generation supporting the iteration of engineering and technical solutions

This characteristic reshapes the generation and evolution model of technical solutions, establishing AI’s core position as a creative thinking partner in engineering design. It constructs a closed loop of “human idea inspiration-machine generation expansion-human-machine collaborative evolution”. Students put forward initial design concepts and core performance indicators (such as “design a bridge structure with high load-bearing capacity and light weight”), and AI can use generative design algorithms to explore a large number of morphological schemes beyond human intuition under given materials, processes, and constraints, generating a series of innovative structural topologies that meet mechanical requirements.

In the design of electronic control systems, AI can automatically generate multiple variants of control logic block diagrams or hardware connection schemes according to functional requirements. However, AI generation is not the end. Students need to use their technical judgment, engineering intuition, and value considerations to evaluate these schemes: assess the manufacturability of different structures under existing processing conditions, compare the reliability, cost, and energy consumption of different control strategies, and comprehensively consider non-technical factors such as aesthetics and environmental integration. On this basis, students can select the optimal scheme for deepening or integrate the advantages of multiple schemes for re-creation. This process forces students to continuously clarify and deepen their design intentions and technical specifications in continuous “dialogue” with AI, transforming vague ideas into precise technical language. Essentially, this is an advanced engineering thinking training. It elevates the focus of learning from imitation and replication to exploration, criticism, trade-off, and innovative synthesis in a broad solution space, greatly stimulating students’ creative potential and cultivating their decision-making ability to seek optimal solutions between technical possibilities and engineering reality.

4.4. Characteristic 4: multimodal formative assessment focused on the development of engineering and technical literacy

Traditional evaluation focuses on the functional realization of final works, making it difficult to gain insight into the process of literacy formation. This characteristic realizes a revolutionary transformation of the evaluation paradigm, that is, constructing a “dynamic map of engineering and technical literacy development” based on whole-process and multi-dimensional behavioral data. The AI system can automatically and unobtrusively collect in-depth behavioral data of students in the project: not only the final version of design sketches but also every iterative evolution from conceptual sketches to precise engineering drawings; not only the final code but also the logical structure and debugging trajectory of different versions during programming; not only the test data of finished products but also the performance comparison basis for material selection, the decision-making reasons for processing technology, the adjustment strategies after experimental failure, and the argumentative dialogues around technical problems in group collaboration. Through educational data mining and learning analytics technology, these multimodal data are transformed into visual descriptions of students’ core literacies[8].

For example, the system can generate a report showing how a student’s “engineering thinking” has evolved from initially focusing only on a single load to comprehensively considering static load, dynamic load, thermal stress, and material creep in the “structural design” project. The evaluation of their “innovative design” is reflected in the frequency and evolution path of breakthrough ideas in their scheme iterations. This evaluation is formative, diagnostic, and developmental. It enables teachers to go beyond judging “whether the work is good or bad” and instead focus on the uniqueness, rhythm, and key nodes of each student’s engineering and technical thinking and ability growth. Thus, it provides unprecedented precise teaching intervention, truly realizing the fundamental purpose of evaluation serving learning and guiding literacy development.

4.5. Characteristic 5: teacher role transformation oriented towards the remolding of the technology and engineering education ecosystem

The in-depth integration of AI has not weakened teachers’ roles but driven their fundamental and strategic sublimation. They have transformed from traditional teaching leaders to architects and value guardians of the engineering and technical learning ecosystem in the intelligent era[2]. Teachers’ professionalism is redefined here, focusing on four core missions. Firstly, as top-level designers, teachers need to carefully construct an open, complex, and challenging macro project framework, seamlessly integrate AI tools (such as CAD/CAE software, simulation platforms, and code generators) into key links of engineering and technical practice, and design rules and processes for human-machine collaboration. Secondly, as precision enablers, relying on the “student literacy digital portrait” generated by AI, teachers can gain insight into individual differences from complex process data, thereby implementing “targeted” guidance—enlightening thinking methods for students encountering bottlenecks in structural mechanics, and providing psychological support and technical strategies for students frustrated in circuit debugging, realizing “teaching students in accordance with their aptitude” in large-scale classes. Thirdly, as leaders of in-depth dialogue, in the context of AI providing a large number of technical schemes, teachers’ core value lies in organizing in-depth discussions, guiding students to conduct critical reflection on the social ethics (such as privacy and safety), environmental sustainability (such as carbon footprint and recycling), and cultural adaptability of technical schemes, ensuring that technological development always serves the overall well-being of humanity. Finally, as guides for value-informed judgment, facing efficient schemes generated by AI, teachers need to cultivate students’ abilities of critical evaluation, responsible decision-making, and value integration, making them understand that “technically feasible” does not equal “engineering reasonable” or “socially desirable”. Therefore, teachers’ roles ultimately focus on nurturing students’ humanistic spirit, engineering ethics, and complex decision-making abilities, ensuring that the educational essence and value beacon of engineering and technical education shine brighter in the efficient learning process empowered by intelligent technologies.

In summary, AI-T&E PBL establishes a new learning paradigm through five iconic characteristics: dynamically generated contexts, adaptive intelligent scaffolding, human-machine collaborative creativity, data-driven literacy portraits, and the professional transformation of teachers' roles. These characteristics are intertwined and organically linked, collectively constructing a learner-centered educational new ecosystem where intelligent technologies and human wisdom are deeply embedded. It aims to more effectively cultivate engineering talents who can adapt to future complex challenges and possess excellent innovation and responsible decision-making abilities.

5. Moving towards practice: implementation suggestions

AI-enabled T&E PBL represents a profound transformation of the educational paradigm. The real realization of its value depends on systematic practical advancement and continuous ecological construction. The following targeted implementation suggestions are proposed from four core dimensions: project design, technical environment, teacher development, and evaluation system, providing practical paths for the implementation of the paradigm.

5.1. Reconstruct project design: from "Task-Driven" to "intelligent situation-driven"

Teachers and curriculum designers need to change their thinking. The core task is no longer to design a detailed, step-by-step operation guide but to construct an "initial problem situation" that can stimulate intelligent interaction and a set of open "generative rules". Project design should reserve space for AI intervention, clearly defining which links require AI for simulation prediction, which decision points need human-machine collaborative scheme generation, and which data will be collected for process analysis. At the same time, project objectives should go beyond specific works and focus more on the development trajectory of students' engineering thinking and core literacies in responding to dynamic and complex contexts, ensuring that project design is highly consistent with the core ideologies of AI-T&E PBL.

5.2. Build technical environment: construct a "Cloud-Edge-Terminal" collaborative intelligent learning space

Schools need to go beyond the configuration logic of traditional laboratories and build an integrated learning space integrating physical workshops, virtual simulation environments, and intelligent data analysis platforms. Specifically, it includes: configuring high-performance computing equipment supporting digital twins and VR/AR; building an Internet of Things sensor network capable of collecting operational behaviors, environmental data, and dialogue content; deploying cloud service platforms covering discipline-specific AI models (such as CAD intelligent assistants, circuit design analyzers, and structural simulation engines). The key is to shift from the traditional thinking of "purchasing hardware" to a systematic thinking of "constructing a sustainable and iterative intelligent educational technology ecosystem", providing stable and efficient technical support for the implementation of AI-T&E PBL.

5.3. Empower teacher development: focus on "human-machine collaborative" teaching design capabilities

The focus of teachers' professional development should shift from the simple use of technical tools to the understanding and application of "AI pedagogy". Relevant training should focus on three core capabilities: first, the ability to design learning tasks with clear division of labor and complementary advantages between humans and machines; second, the ability to interpret learning situation data reports provided by AI and implement precise intervention based on them; third, the ability to guide students in critical review, ethical discussion, and value choice in the context of AI generating massive information and schemes. Through training, teachers can truly become "chief designers" of human-machine collaborative learning processes and "guides" for students' humanistic spirit growth, adapting to the core requirements of the new paradigm for teachers' roles[9].

5.4. Innovate evaluation system: establish evidence-based literacy development assessment

Evaluation reform should advance simultaneously with project implementation and be deeply coupled. On the one hand, it is necessary to develop a digital portfolio system connected with intelligent learning platforms to realize the automatic collection and analysis of multimodal process data; on the other hand, it is necessary to optimize evaluation criteria, expanding from single work outcome indicators to a comprehensive indicator system including multi-dimensional literacy development evidence such as "iteration trajectory of scheme innovation", "effectiveness of human-machine collaboration", and "changes in systematic thinking complexity". At the same time, it is necessary to establish and improve evaluation ethical norms, clarify the boundaries of data use, ensure that data serves the core goal of students' development, and strictly protect students' privacy, realizing the unity of scientificity and ethics in evaluation.

6. Conclusion

AI-enabled technology and engineering project-based learning is leading a comprehensive innovation covering educational concepts, teaching methods, and educational ecosystems. The successful practice of this paradigm not only requires advanced technical tools as support but also requires educators to carry out systematic design with an open mind, conduct in-depth role empowerment for teachers, and achieve breakthrough reconstruction of the evaluation system.

Looking forward to the future, this new paradigm integrating human wisdom and machine intelligence is expected to cultivate the next generation of engineering innovators with exquisite skills, systematic thinking, innovative courage, and humanistic care. It will enable them to confidently lead a future world co-shaped by humans and intelligent agents, injecting lasting impetus into the high-quality development of technology and engineering education.

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