DOI: 10.66069/ojspub.1137261014

A New Quality Education Paradigm for Mechanical Engineering Based on the Concept of "Industry-Education Digital Twins + Intelligent Education"

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Abstract: ***In response to the critical demands for cultivating new-quality talent in the digital-intelligent era during the new developmental phase of marine engineering equipment, and synthesizing constructivist learning theory, situation awareness theory, the conceive-design-implement-operate (CDIO) framework, and evidence-based pedagogical concepts, this study proposes an interdisciplinary new-quality talent cultivation paradigm anchored by collaborative research on marine gear transmission systems. It explores novel teaching-and-learning modalities enabled by digital-intelligent technologies, such as knowledge graphs, generative artificial intelligence (GAI), and digital twins-to foster teacher-student-machine ternary synergy, while systematically investigating their adapted digital curriculum design models, instructional content architectures, and implementation pathways. Aimed at leveraging university digital curricula as a strategic entry point to resolve the overarching challenges of new-quality talent development, this work bolsters the digital transformation of higher education and accelerates the fostering and advancement of new-quality productive forces.***

Keywords: New-Quality Education, Industry-Education Digital Twins, Teacher-Student-Machine Synergy, Artificial Intelligence.

1. Introduction

Against the backdrop of new-quality productive forces, collaborative talent cultivation through industry-education integration serves as a vital pathway for higher education institutions to align with industrial demands and advance the supply-side reform of talent training. Presently, industry-education integration has entered a stage of deep integration, marked by closer university-enterprise cooperation and more extensive resource sharing. However, at the current stage, industry-education integration predominantly relies on shallow, contract-based project cooperation, characterized by short-term and loosely coupled relationships. Curriculum instruction is primarily governed by university-defined training programs, rarely designing course content around authentic corporate production realities and engineering challenges, while merely touching upon relevant enterprise technical knowledge and production conditions in a popular-science manner during lectures [1].

Concurrently, the intelligent transformation and digital upgrading of industries have presented new opportunities for digital-intelligent development for China's industrial sector, creating an expansive demand for digital-intelligent talent. Digital transformation has ushered in the Education 5.0 era, opening up a new educational landscape, novel multimodal learning experiences, and a new paradigm of human-machine collaboration, while accentuating subjectivity, inclusivity, equity, sustainability, resilience, proactive agency, and solidarity in learning [2-3]. Consequently, deepening novel models of digital-intelligent industry-education integration and forging new modalities of digital-intelligent education and pedagogy will effectively facilitate the transition from "Made in China" to "Created in China." In this process, innovation-driven education aims to bridge the divides among research, education, innovation, and production, thereby fostering their synergistic co-development. Furthermore, integrated innovation education fosters creative ideas and problem-solving schemes through the profound fusion of tool systems, content structures, and cognitive modes, shaping transdisciplinary mental frameworks and realizing the practical translation and cross-boundary synthesis of knowledge-competency systems [4]. Wu et al. [5] attempted to construct a practical pathway of "response-transformation-implementation-enhancement-innovation-safeguard" for digital and intelligent technologies empowering new-quality education, spanning dimensions including concept reinvention, environment reshaping, platform establishment, literacy improvement, pathway generation, and institutional guarantees. Luo et al. [6] examined the prerequisites for multimodal large models to drive disciplinary knowledge graphs, exploring the fundamental connotations and structural frameworks of multimodal disciplinary knowledge graphs from an evolutionary perspective.

The expansion of new-quality productive forces inherently calls for the cultivation of new-quality talent. As the fundamental building block of talent cultivation, the digital transformation of curricula has emerged as a widely recognized imperative across the higher education sector. Connecting academic majors with classroom instruction, the curriculum serves as the fundamental unit of digital education and new-quality talent development, standing at the core of cultivating innovative talent in the digital-intelligent era. Ding et al. [7] employed knowledge graphs to precisely capture the industry's competency requirements for higher engineering education, mapping these demands onto curricular knowledge points to construct a bidirectional model enabling competency

attainment assessment and continuous improvement across industry and education. In response to the multidisciplinary cross-cutting characteristics of engineering systems in the digital-intelligent era, Academician Yang et al. [8] developed a core curriculum framework oriented toward the synergistic cultivation of learners across four scientific paradigms-experimental observation, theoretical deduction, computational simulation, and data-driven approaches ("X-4 paradigm")-providing valuable reference points for the ongoing wave of higher education reform.

Grounded in curriculum, instruction and digital education theories, Xie et al. [9] delineated a theoretical logic of "value guidance-structural remodeling-digital-intelligent empowerment" for university curriculum digital transformation in the intelligent era. Guided by evolving perspectives on knowledge and talent in the digital-intelligent era, Wang et al. [10] articulated a curricular development philosophy encompassing thinking and competency cultivation, problem-driven knowledge systems, digital-intelligence-enabled personalized learning experiences, teacher-student co-created contextual learning ecologies, and outcome-oriented comprehensive curriculum quality evaluation. Drawing upon the worldview of engineering philosophy, Academician Hu et al. [11] deconstructed the relationship between engineering and mechanics, elucidating the fundamental logic, essential content, and operational pathways of engineering mechanics methodology. Addressing persistent challenges such as structural imbalances and insufficient specificity in digital resource provision, restricted multidisciplinary expansion, and the disconnection between educational technology and instructional content, Huang et al. [12] leveraged the course Equipment Systems Engineering to formulate a three-dimensional instructional objective, reconstruct an integrated two-sided, case-threaded content structure, and propose a conceive-design-implement–operate (CDIO) practical cultivation model for engineering competencies. Xi et al. [13] synthesized CDIO and STEM (science, technology, engineering, and mathematics) educational principles to devise an innovation-oriented practical teaching design driven by engineering thinking. From a five-dimensional learning design perspective—encompassing collaborative agents integrated with large AI models, technology-rich mediation, activity orchestration supporting multi-agent interactions, large-model-generated learning scenarios, and content threads reflecting the transformations of the digital and intelligent era-Zhu et al. [14] investigated and deciphered the operational mechanisms constituting the "wisdom-integrated classroom." Furthermore, to resolve the prevalent pedagogical dilemma of being "data-rich but information-poor," Wang et al. [15] thoroughly probed the connotations and generalized conceptual model of digital-intelligent evidence-based teaching and research, along with data-driven instructional decision-making mechanisms.

Accordingly, to address the strategic demands for digital innovation in the modern engineering equipment manufacturing industry, curriculum digital transformation serves as a pivotal leverage point to drive the multi-tiered synergistic linkage across the "specialty-curriculum-classroom" system, thereby advancing the iterative evolution of the new-quality innovative talent cultivation paradigm. As a core course within the coherent theory-practice integrated cultivation framework for mechanical engineering majors, Modern Mechanical Design Method encompasses intersecting interdisciplinary domains, including mechanical system dynamics, the finite element method, data-driven techniques, and model-based systems engineering (MBSE) methodology, aimed at bolstering students' digital innovation capacities in high-end equipment R&D. Therefore, taking the digital-intelligent and integrated-innovation instructional design of Modern Mechanical Design Methods as an exemplar, this study adheres to the ethos of giving equal emphasis to engineering practice and theoretical inquiry, ultimately fostering students' sustainable capacity for lifelong learning.

2. Dilemmas and Breakthrough Logic in Mechanical Engineering Talent Cultivation

2.1 How to Strengthen Engineering Science Thinking and Foster Students' Proactive Innovation Awareness?

Taking the "collaborative research on marine gear reducers" as an entry point, this approach accentuates the engineering-science orientation of both curriculum content and instructional design. By leveraging knowledge graphs to steer the profound cross-disciplinary integration of multidisciplinary knowledge architectures within the practice of "engineering equipment system design," and utilizing human-machine collaboration to facilitate personalized learning, it stimulates enduring learning interest and digital-intelligence-enhanced learning capacity, thereby establishing a powerful catalyst for students' proactive innovation. Furthermore, a digital-intelligent evidence-based instructional evaluation mechanism is introduced to promote learning through assessment, thereby propelling learners' continuous self-advancement and value accrual.

2.2 How to Reshape Curriculum Structure and Strengthen the Cultivation of Students' Engineering Systems Thinking?

Modern marine gear transmission design exhibits essential engineering systems characteristics, including integrity, purposiveness, dynamism, openness, and human-centeredness. However, conventional instructional content remains constrained by rigid disciplinary boundaries and ossified curricular architectures, leading to the fragmentation of course knowledge construction. Consequently, students struggle to synthetically apply acquired knowledge to resolve complex engineering problems across the demonstration, development, and experimentation stages of modern equipment. By fully leveraging the empowering synergies of "AI + knowledge graphs," multidisciplinary content is modularly orchestrated and linked with multimodally represented learning resources. Through human-machine collaboration, a contextualized practice space is forged to support students in conducting collaborative inquiry and achieving meaning generation, thereby deeply cultivating and shaping their systems-science thinking.

2.3 How to Update the Conception of Knowledge Production and Leverage Digital-Intelligent Pedagogical Modalities to Support Innovative Practice?

Innovative design practice represents an essential pathway toward mastering Modern Mechanical Design Methods; however, numerous experimental and practical endeavors are hampered by the persistent dilemmas of being "prohibitively expensive and operationally unfeasible." The lack of a comprehensive multidisciplinary collaborative design system precludes multi-round engineering design iterations, impeding the effective breakthrough of the barrier between theory and practice. Digital twin technology enables higher-fidelity design and simulation, substantially curtailing the requisite cycles of trial fabrication and physical testing while reducing R&D expenditures. Building upon the established "gear transmission digital twin system," generative artificial intelligence is leveraged to train customized "domain-specific vertical large models." This empowers learners to engage in multifaceted learning activities, including experimental exploration, contextual immersion, and collaborative inquiry throughout the design of marine gear transmission systems.

3. A New-Quality Educational Paradigm for Mechanical Engineering

Addressing prominent pedagogical dilemmas in cultivating interdisciplinary innovative talent in the AI era, this study takes the collaborative research on marine gear transmission systems as the guiding vehicle and digital-intelligent technologies as the foundational support. By reconstructing instructional content, innovating wisdom-integrated pedagogical models, deploying wisdom-integrated instructional modalities, and implementing wisdom-integrated educational evaluation, as illustrated in Figure1, it advances the "three enhancements"-namely, students' proactive innovation consciousness, engineering systems thinking competence, and support modalities for innovative practice. Consequently, it progressively transcends the barriers between fundamental theory and engineering application, establishing a new-quality innovative talent cultivation paradigm for mechanical engineering.

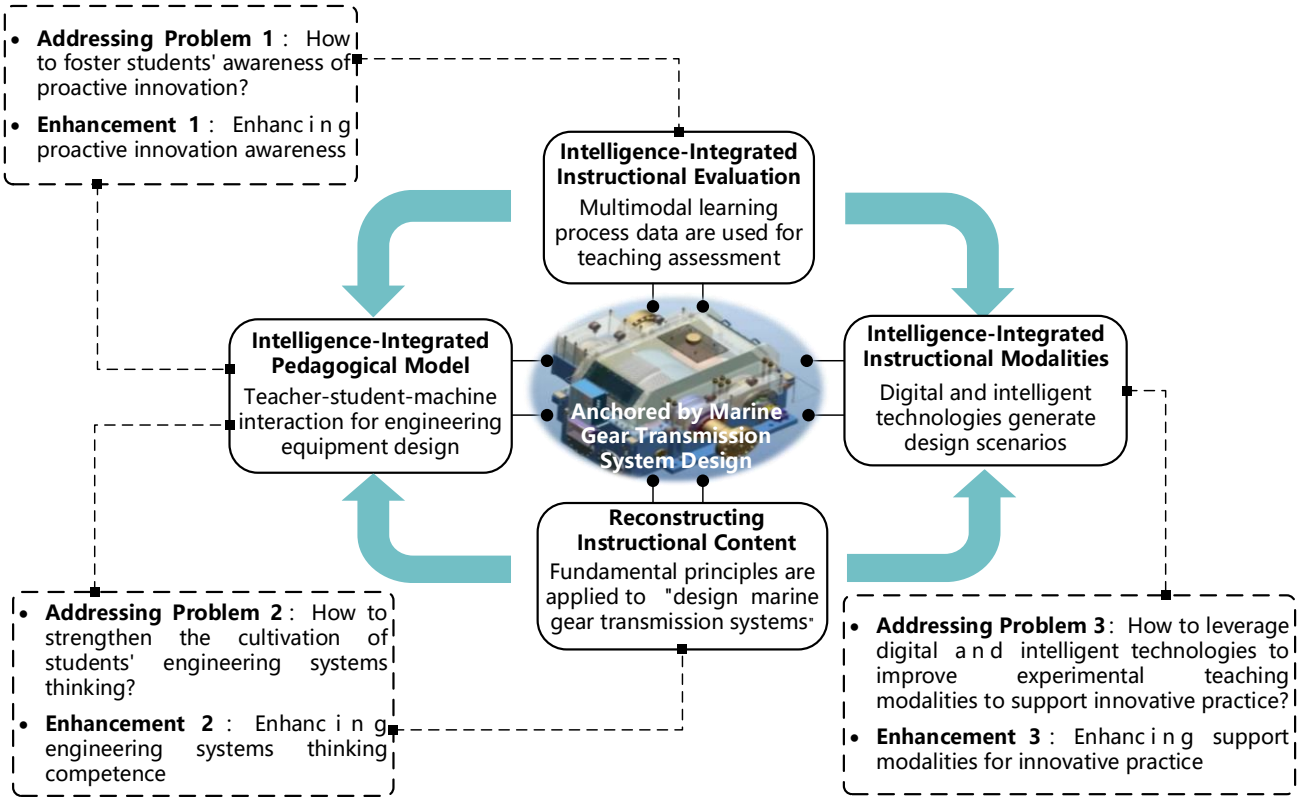


Figure 1: New-Quality Educational Paradigm for Mechanical Engineering

3.1 Reconstruction of Instructional Content

To align with disciplinary evolution and industrial strategic demands for modern equipment, and anchored by collaborative research on marine gear transmission systems, instructional content is dynamically reconstructed and iteratively upgraded based on "AI + knowledge graphs" along the knowledge-competency trajectory of innovative talents' cognitive development. Through the convergent aggregation of "whole-person development (Value graph, V)," "talent development (Knowledge graph, K)," "craftsmanship cultivation (Skill graph, S)," and "collective development (Quality graph, Q)" a seamless vertical articulation and horizontal coordination among knowledge acquisition, competence cultivation, and interdisciplinary literacy are realized, ultimately achieving an organic unity of ideological-professional synthesis and personalized pedagogical provision.

By introducing engineering cases via diversified channels and constructing the skill/competency graph (S) guided by engineering science, the linkage between course instruction and five core research paradigms—experimental observation, theoretical deduction, computational simulation, data-driven approaches, and artificial intelligence-is substantially reinforced. Furthermore, by profoundly mining the "three outlooks (worldview, outlook on life, and values) and one methodology" embedded within the curricular content thread, students' systems-science thinking and systems-engineering methodology are tempered and reshaped. Through the establishment of authentic case-based scenarios, students' core literacy in collaborative problem-solving and

collaborative tackling of key problems (Quality graph, Q) is nurtured, thereby promoting synergy between the knowledge graph and the value graph in talent cultivation.

3.2 Wisdom-Integrated Pedagogical Model

Centered on collaborative research on marine gear transmission systems and guided by the constructivist learning theory framework, a "four-pillar mentorship team"-encompassing moral education, disciplinary expertise, engineering practice, and international perspectives-is established. In conjunction with generative artificial intelligence, an exploratory space integrating theoretical application and engineering practice is established. Leveraging the graph-based relationships among knowledge points, competency points, ideological and political education points, and quality points, a CLEs (constructivist learning environments)-CDIO case-based teaching method supporting the autonomous construction of competencies is explored from the perspective of human-machine collaboration. By organizing sequences of teaching-and-learning activities in a scenario-based format, it facilitates collaboration among teachers and students, among students, and between students and machines, enabling them to jointly participate in knowledge and competency construction.

A vertical application mechanism model of generative artificial intelligence in immersive learning environments is constructed to develop scenario-specific generative artificial intelligence tailored to marine gear transmission system design. Grounded in knowledge graphs and digital textbooks, the DeepSeek model is utilized to train a "domain-specific vertical large model" suitable for the design of the aforementioned engineering equipment. By associating the curriculum standard ontology, disciplinary knowledge ontology, and learning resource ontology, students can utilize this model to interpret literature, analyze data, evaluate models, and conduct logical reasoning, thereby strengthening their training in scientific paradigms, interdisciplinary thinking, and engineering thinking.

3.3 Wisdom-Integrated Instructional Modalities

An intelligent design and operation-and-maintenance (O&M) system for marine gear transmission systems is developed to drive the transformation of innovative practice from a "waterfall" model to "agile iteration." Incorporating digital-twin-based research outcomes into teaching, an integrated design-and-O&M system for marine gear transmission devices is established, covering multidisciplinary knowledge such as overall architecture, transmission, vibration and noise reduction, and shock resistance. This creates an immersive practical environment to construct and cultivate students' engineering literacy, reducing a single design iteration cycle from several weeks to a few hours. This ensures that students can conduct innovative practice involving multidisciplinary trade-offs, iterations, and synthesis, progressively building their systems-science thinking competence.

Relying on the constructed intelligent design and O&M system for marine gear transmission systems, and integrating situation awareness theory with constructivist learning theory, this study investigates a collaborative practical teaching method based on digital twins. By examining the scenario-based construction paradigms of digital twins, the instructional models of educational digital twin applications are analyzed across theoretical foundations, learning environments, learning activities, and model constitutive elements, constructing a well-adapted conceptual framework of pedagogical methods. This stimulates the deep cross-integration of students' interdisciplinary knowledge and scientific research paradigms, and ultimately achieves meaning generation.

3.4 Wisdom-Integrated Instructional Evaluation

Integrating blockchain technology and multimodal data fusion techniques, an instructional evaluation system based on multi-source evidence and personalized value-added assessment is constructed. By means of manual value judgment, machine data sensing, and human-machine collaborative diagnosis and improvement, learners' value formation, knowledge acquisition, and competency attainment are comprehensively evaluated. By integrating and leveraging the value of evaluation data, trustworthy evidence is extracted to provide various curriculum stakeholders with a basis for intervention and improvement, thereby promoting the shift of curriculum diagnosis and improvement decisions from empirical judgment to scientific analysis.

Grounded in the concepts of "evidence-based education" and "value-added assessment," corresponding evaluation indicators are formulated around ideological and political values, knowledge, competencies, and comprehensive qualities. Mapping rules connecting evaluation indicators with learning process data are established, thereby proposing an evidence-based diagnostic and personalized value-added assessment strategy encompassing assessment nodes, methods, evidentiary bases, elements, and standards. Based on the analysis of existing teaching cases, this study explores the connotations and actionable models of digital-intelligent evidence-based teaching and research. By combining value-added assessment with process evaluation, a data-driven human-machine collaborative diagnostic mechanism is formed to achieve agile diagnosis and improvement of instructional problems, ensuring alignment between teaching and learning.

4. Conclusion

Oriented toward the new-quality demands for cultivating interdisciplinary design talent in marine engineering equipment, this study takes integrated innovation education as the foundational pivot for transformative change to construct a new-quality educational paradigm for interdisciplinary innovative talent. By adopting engineering requirements as the guiding thread of practical training, it establishes a design-thinking-driven, wisdom-integrated pedagogical model and creates a digital-twin-supported hybrid practical arena. Furthermore, leveraging digital-intelligent evidence-based analytics as an agile transformative mechanism, an innovative evaluation system characterized by multi-source evidence-based verification and personalized value-added assessment is established. These three dimensions complement and reinforce one another, collaboratively forging a digital-intelligence-driven higher education ecology

for mechanical engineering disciplines.

Taking the digital transformation of curricula underpinned by industry-education integration as a strategic entry point, this study proposes a paradigm wherein scientific research outcomes and digital-intelligent technologies synergistically empower new-quality education. This approach deepens industry-education integration and university-enterprise cooperation, seamlessly bridges the talent cultivation chain with the industrial service chain, and ultimately propels the systemic reform of innovative talent cultivation models in Emerging Engineering Education.

Acknowledgement

This work is supported by Heilongjiang Province Graduate Course Ideological and Political High Quality Construction Project under Grant No. HLJYJSZLTSGC-KCSZAL-2024-015, Heilongjiang Provincial Higher Education Association Project under Grant No. 24GJZXC035 and No.2026xm51, and Harbin Engineering University Teaching Reform Project under Grant No. JGYB20250701.

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