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Research on AI-Empowered Digital Innovative Design Practice Teaching Reform for Mechanical Majors

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ABSTRACT: *The rapid development of intelligent manufacturing and generative artificial intelligence has profoundly changed the methodology and workflow of mechanical product design, and has also set new requirements for training innovative design talents in mechanical majors. Aiming at the common problems in current practice teaching for mechanical majors —content lagging behind the digital design paradigm, instructor-centered methods, disconnection between virtual and physical platforms, and single evaluation modes—this paper, guided by the outcome-based education (OBE) philosophy, constructs a five-in-one AI-empowered practice teaching reform scheme for digital innovative design, comprising "objective restructuring, content restructuring, method restructuring, platform restructuring, and evaluation restructuring." It systematically presents the reform content, four-stage implementation steps, and a three-dimensional multi-evaluation method of "process + outcome + value-added." The scheme positions artificial intelligence as a cognitive partner rather than a replacement tool in design capability development, and can provide an operable reference for the intelligent teaching reform of mechanical majors.*

Keywords: *Mechanical majors, Artificial intelligence, Digital innovative design, Teaching reform, Multi-evaluation, Talent cultivation*

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I. INTRODUCTION

The accelerated integration of intelligent manufacturing and the new generation of artificial intelligence is profoundly reshaping the paradigm of mechanical product design. The traditional design process, which relies mainly on experience-based design, two-dimensional drawings and manual verification, is gradually shifting toward a new process of "three-dimensional digital definition, virtual simulation verification, data-driven optimization, and generative intelligent design" [1,2]. Technologies such as large language models, digital twins and virtual simulation have entered every stage of product R&D, and the industry's demand for interdisciplinary talents who understand mechanical design principles and can use digital and intelligent tools for innovative design is becoming increasingly urgent [2,3].

However, current practice teaching for mechanical majors is clearly mismatched with this transformation. First, the teaching content lags behind: most courses still take traditional reducer design, manual calculation and drawing as the main carriers, with insufficient coverage of modern design methods such as parametric design, multi-objective optimization and digital twin verification, so students can hardly perceive the full picture of the digital design paradigm in their courses [1,2]. Second, teaching methods are monotonous, dominated by instructor lectures and verification experiments; students passively receive knowledge and lack self-directed inquiry and iterative optimization training based on real problems [4,5]. Third, the practice platform disconnects the virtual and the physical: complex objects such as large equipment and automated production lines are difficult to carry out physically, while virtual simulation platforms generally lack linkage with physical equipment [6,7]. Fourth, evaluation is single-dimensional, mostly based on design specifications and drawings through summative assessment, which can hardly objectively reflect students' design process, innovative contribution and collaborative ability [8]. Meanwhile, students generally lack AI literacy: they "can use but cannot wisely use" AI tools, and even directly apply generated outputs without critical reflection [8].

Since the Ministry of Education launched the AI-empowered education initiative, universities have conducted extensive explorations around "AI + courses" and "AI + practice." How to systematically build an AI-empowered digital innovative design practice teaching system for mechanical majors and clarify "what to reform, how to reform, and how to evaluate" has become an urgent question for Emerging Engineering education. On the basis of reviewing related research over the past five years, and guided by the outcome-based education philosophy, this paper constructs a five-in-one reform scheme of "objective–content–method–

platform–evaluation restructuring," and focuses on the reform content, implementation steps and evaluation methods, so as to provide an operable reference for the intelligent teaching reform of mechanical majors.

II. RESEARCH FOUNDATION AND LITERATURE REVIEW

Over the past five years, research on AI-empowered teaching for mechanical majors has mainly unfolded along four directions, as shown in Table 1.

Table 1 Clustering of AI-empowered teaching research for mechanical majors in the past five years

Theme	Main Approaches and Viewpoints	Implications for This Study
AI integrated into course content	Neural network algorithms are introduced into reducer parameter optimization and design report evaluation; a trinity content system of "basic theory + intelligent technology + engineering practice" is reconstructed [1-3].	Content restructuring should be systematically designed along new technologies as the main thread.
Digital platforms and virtual–physical integration	An intelligent virtual production workshop, a digital twin practice platform and a virtual–physical joint debugging system are built to compensate for the insufficiency of physical experiments on large equipment [6-7,9].	Platform construction should be tiered and progressive, with virtual–physical complementarity and alignment with course groups.
AI tools integrated into teaching and learning	AI teaching assistants, knowledge graphs and teaching agents are constructed to realize personalized learning paths and process feedback [5,10-11].	Teaching methods should transform toward human–machine collaboration, emphasizing higher-order thinking cultivation.
Cultivation system and evaluation reform	Data-driven OBE 2.0 experimental teaching, digitally-empowered differentiated teaching, and emerging-engineering transformation paths for traditional courses are proposed [12-14].	Evaluation should be process-oriented and data-driven, forming a closed loop of continuous improvement.

As shown in Table 1, at the course-content level, researchers have attempted to introduce AI methods into mechanical courses. At the practice-platform level, the teaching application of virtual simulation and digital twin technologies has deepened. At the teaching-and-learning level, AI teaching assistants, knowledge graphs and teaching agents have become hot topics. At the talent-cultivation-system level, existing research shows three features: first, most studies focus on localized reform of a single course or a single teaching link, lacking a systematic scheme that connects "objectives–content–method–platform–evaluation"; second, implementation paths are mostly principle-level descriptions, lacking a phased, verifiable roadmap; third, evaluation reform mostly remains at the level of indicator listing, and the closed-loop mechanism of feeding evaluation data back into teaching is still unclear. Therefore, taking the cultivation of digital innovative design capability as the main thread, this paper proposes an integrated reform scheme, focusing on three interconnected core questions: what to reform, how to implement, and how to evaluate.

III. OVERALL DESIGN OF THE TEACHING REFORM

The theoretical basis of this reform scheme includes three aspects. The first is the outcome-based education philosophy, which designs teaching objectives and teaching links in reverse according to graduation requirements, and measures teaching effectiveness by degree of capability attainment [12,13]. The second is constructivist learning theory, which emphasizes that learners actively construct knowledge in real and complex design tasks, and project-based teaching is an appropriate carrier. The third is human–machine collaborative cognition theory, which positions artificial intelligence as the student's "cognitive partner": AI undertakes lower-order cognitive tasks such as retrieval, generation and diagnosis, while students focus on higher-order cognitive activities such as scheme judgment, trade-off decision-making and innovative design, avoiding "technology replacing thinking."

Accordingly, the reform follows four design principles: capability-output orientation, decomposing digital innovative design capability into observable and assessable behavioral indicators; real-project carrier, using an integrated project chain to connect knowledge, ability and literacy; AI as cognitive partner, upholding the unity of instrumental rationality and educational rationality, and guiding students from "being able to use AI" to "being good at using AI"; and data as the basis for improvement, taking process data as evidence for teaching diagnosis and continuous improvement. The overall framework of the teaching reform is shown in Figure 1: taking "digital innovative design capability oriented to intelligent manufacturing" as the training objective, five restructurings of objective, content, method, platform and evaluation work in synergy; taking the three-level project group of "typical transmission device design — reducer multi-objective optimization — intelligent equipment innovative design" as the practice carrier; and AI technologies such as large language models, knowledge graphs, digital twins and virtual simulation providing full-process empowerment.

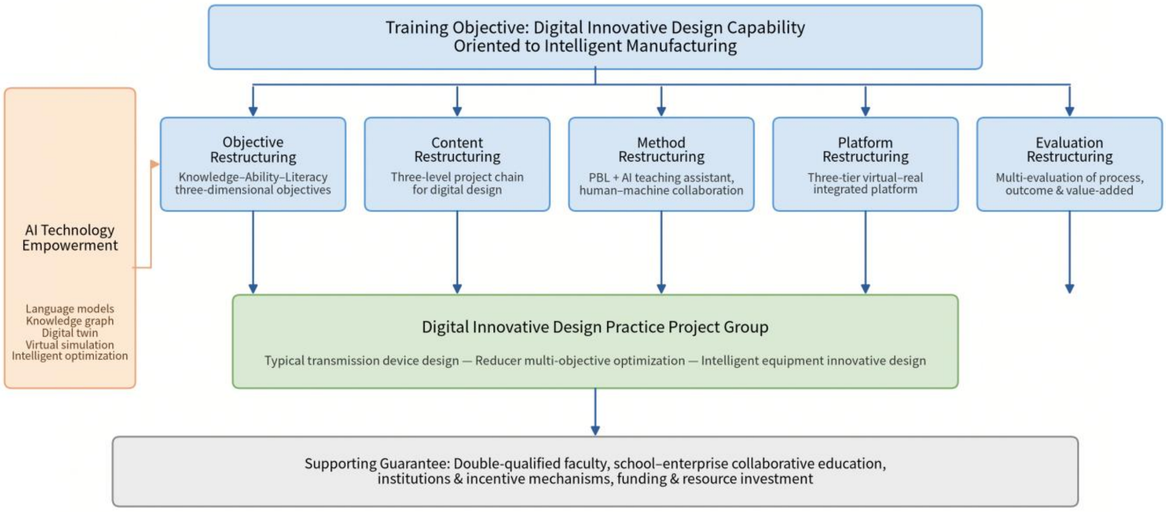

Fig. 1 Overall framework of the teaching reform

3.1 Design of the Reform Content System

3.1.1 Objective Restructuring

A three-dimensional objective system of "knowledge–ability–literacy" is established. In the knowledge dimension, students are required to master the basic principles of modern design methods and the fundamentals of artificial intelligence technology, and to understand the logic of data, models and algorithms in the digital design process. In the ability dimension, five key abilities are focused on: digital modeling, intelligent optimization, simulation verification, innovative design and engineering expression, which constitute the connotation of digital innovative design capability. In the literacy dimension, emphasis is placed on engineering ethics, norms for AI use, craftsmanship spirit and team collaboration [2,3]. The three-dimensional objectives are further refined at the course level into measurable and assessable attainment indicators, serving as the common basis for teaching and evaluation.

3.1.2 Content Restructuring

A three-level digital innovative design project chain of "foundation–intermediate–comprehensive" is constructed, as shown in Table 2. The foundation module takes the digital design of typical transmission devices as the project, training the standard procedures of parametric modeling and finite element verification. The intermediate module takes reducer multi-objective optimal design as the project, introducing intelligent optimization methods such as neural networks and genetic algorithms, and verifying design performance through virtual simulation and digital twins. The comprehensive module takes innovative design of intelligent equipment as the project, integrating generative design, virtual–physical joint debugging and agent collaboration, and linking to discipline competitions and real enterprise projects. Meanwhile, a course knowledge graph and an AI-assisted knowledge base are built, embedding new technologies such as topology optimization, additive manufacturing constraints and digital twin modeling into the course in a modular manner, and dynamically updating them according to technological iteration and enterprise feedback.

Table 2 Three-level project chain for digital innovative design

Module	Typical Project	Digital and AI Technologies Involved	Main Ability Objectives	Linked Courses
Foundation module	Digital design of typical transmission devices	Parametric 3D modeling, finite element verification,	Digital modeling, engineering expression	Mechanical Design, 3D CAD

		standard part library		
Intermediate module	Reducer multi-objective optimal design	Neural network / genetic algorithm assisted optimization, virtual simulation, digital twin verification	Intelligent optimization, simulation verification	Mechanical Design Course Design, Theory of Machines and Mechanisms Course Design
Comprehensive module	Innovative design of intelligent equipment	Generative design, virtual–physical joint debugging, teaching agent collaboration	Innovative design, system integration	Mechanical Innovative Design, Graduation Design, Discipline Competitions

3.1.3 Method Restructuring

A human–machine collaborative teaching model of "PBL + AI teaching assistant" is promoted. Taking project tasks as the main thread, a cyclic teaching method of "requirements analysis — scheme generation — simulation optimization — virtual–physical verification — iterative improvement" is constructed, enabling students to experience the complete digital design process in real design problems. Task gradients are designed according to the principle of "layered foundation tasks, optional intermediate tasks, and open comprehensive tasks," accommodating the personalized development of students with different backgrounds. Relying on the course knowledge base, the AI teaching assistant provides 24-hour Q&A, personalized exercise push and process diagnosis, liberating teachers from repetitive Q&A so that classroom time focuses on higher-order thinking guidance and engineering judgment training. Flipped classrooms are adopted to organize pre-class self-study, in-class discussion and after-class extension, while mechanisms for AI-use norms and academic integrity education are established simultaneously, clarifying the attribution and boundaries of using generated content.

3.1.4 Platform Restructuring

A three-tier progressive practice platform of "virtual simulation + digital twin + physical experiment" is built. The virtual simulation platform supports foundational training in parametric modeling, kinematic and dynamic simulation, and finite element analysis. The digital twin platform realizes real-time mapping and joint debugging between virtual models and physical equipment, compensating for the difficulty of physically carrying out large equipment [15]. The physical experiment platform retains necessary physical verification links, forming a training chain of "virtual first, physical second, virtual and physical complementing each other." Meanwhile, course resource libraries, enterprise case libraries and AI knowledge bases are built; through school–enterprise collaboration, real enterprise products, engineering standards and industry mentors are introduced to effectively connect teaching scenarios with industrial scenarios.

3.1.5 Ideological and Political Integration

Curriculum ideological and political education runs through the entire project chain. Cases of nationally strategic heavy equipment and key core technology breakthroughs in intelligent manufacturing are embedded into digital design tasks, guiding students to understand the contemporary requirements of independent and controllable design and sci-tech self-reliance. Combined with engineering standards and manufacturing constraint training, the program cultivates craftsmanship spirit of excellence and a rigorous, realistic engineering ethics consciousness, achieving the organic unity of knowledge transmission, ability cultivation and value shaping.

3.2 Implementation Steps

The reform advances in four rolling stages of "preparation–pilot–promotion–consolidation." The implementation road map is shown in Figure 2. Each stage follows the closed-loop management of "plan–do–check–act," with clear milestones and acceptance criteria.

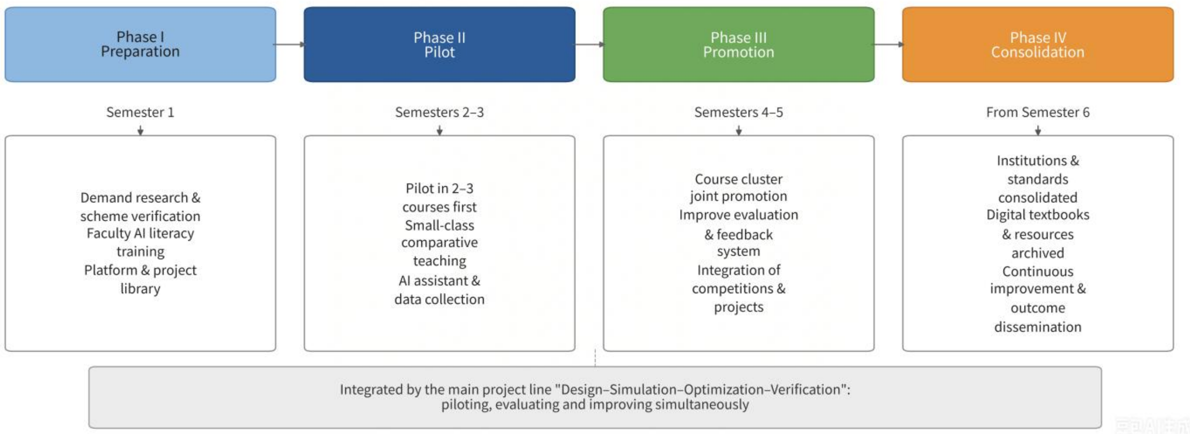

Fig. 2 Implementation road-map

Phase I is the preparation period (Semester 1). Main tasks include: conducting industry and enterprise investigations and graduate follow-up surveys to clarify the specific connotation of digital innovative design capability and job requirements, and revising the training program after argumentation; organizing faculty AI literacy workshops and digital tool training to form a consensus within the teaching team; completing the selection and deployment of virtual simulation and digital twin platforms, and building the three-level project library, course knowledge base and evaluation rubrics, laying the foundation for the pilot implementation.

Phase II is the pilot period (Semesters 2–3). Three courses, namely Mechanical Design Course Design, Theory of Machines and Mechanisms Course Design, and Digital Design, are selected for the pilot. In each course, an experimental class and a control class are set up for comparative teaching. The AI teaching assistant and process data collection system are deployed to record students' operation trajectories, iteration processes and stage outcomes. Small-scale evaluation tests are conducted to verify the reliability and validity of the indicator system, and teaching design is dynamically adjusted according to feedback.

Phase III is the promotion period (Semesters 4–5). Reform experience is jointly promoted to course groups of Mechanical Design, Mechanical Manufacturing, and Mechanics, realizing the connection and continuity of the project chain across different courses. Discipline competitions, the National College Students' Innovation and Entrepreneurship Training Program, and enterprise projects are incorporated into comprehensive projects to expand project sources. The AI teaching assistant, personalized learning paths and evaluation feedback system are improved to realize data-based stratified teaching and precise intervention.

Phase IV is the consolidation period (from Semester 6 onward). Mature experience is elevated into institutions and standards, forming course teaching standards, project guidance manuals and evaluation implementation plans. Digital textbooks and online resources are compiled to deposit reusable teaching assets. An annual diagnosis-and-improvement mechanism is established to continuously optimize the scheme according to evaluation data and graduate feedback, and to radiate the outcomes within and beyond the university.

3.3 Evaluation Methods

3.3.1 Evaluation Philosophy

The evaluation reform adheres to equal emphasis on the three dimensions of “process + outcome + value-added.” Process evaluation focuses on evidence of performance at each project stage; outcome evaluation focuses on the quality of final deliverable; value-added evaluation takes the pre-eminent test as a baseline to measure actual capability progress, avoiding “one exam decides the grade.”

3.3.2 Indicator System

This paper constructs a multi-dimensional evaluation indicator system for digital innovative design capability, as shown in Table 3, covering five first-level indicators. The knowledge mastery dimension examines understanding of design principles and new-technology knowledge through stage quizzes and in-class Q&A. The digital design ability dimension relies on deliverable files and platform auto-scoring to examine the standardization of 3D modeling, correctness of simulation analysis and compliance of drawings. The innovative practice dimension is jointly reviewed by teachers and enterprise experts on scheme novelty, number of optimization iterations and degree of deliverable completion. The process performance dimension integrates teacher observation, peer review and platform process data. The comprehensive literacy dimension examines engineering ethics, AI-use norms and expression ability through reflection reports and defense. Weights follow the principle of "ability orientation and equal emphasis on process," and are rolling-calibrated based on pilot data.

Table 3 Multi-dimensional evaluation indicator system for digital innovative design capability

First-level Indicator	Second-level Indicators	Weight	Subjects and Methods
Knowledge mastery	Understanding of design principles; application of new-technology knowledge	15%	Teacher: stage quizzes, in-class Q&A
Digital design ability	Standardization of 3D modeling; correctness of simulation analysis; compliance of drawings	25%	Teacher + AI platform: deliverable review, automatic platform scoring
Innovative practice	Scheme novelty; number of optimization iterations; degree of deliverable completion	25%	Teacher + enterprise experts: scheme review, defense
Process performance	Participation; collaborative contribution; on-time rate of stage tasks	20%	Teacher + peer review + platform process data
Comprehensive literacy	Engineering ethics; AI-use norms; expression and reflection	15%	Teacher + student self-assessment: reflection report, defense

3.3.3 Implementation Approach

Evaluation subjects are diversified, adopting a combination of "teacher evaluation + peer review + enterprise expert review + AI platform automatic collection." Process data are automatically collected and archived by the teaching platform to form a traceable evidence chain of learning. Enterprise engineers are introduced to review deliverable from the perspectives of engineering feasibility and process-ability, promoting alignment between learning outcomes and industrial needs. Project defense and outcome exhibitions are organized at the end of the term to examine comprehensive expression and reflection ability, ensuring that evaluation covers the complete design chain.

3.3.4 Feedback Closed Loop

Evaluation results are not used to "label" students, but are fed back into teaching to form a continuous improvement closed loop. The multi-dimensional evaluation system and feedback loop are shown in Figure 3. Attainment analysis is conducted regularly to identify weak capability points and teaching links, on the basis of which project difficulty, guidance strategies and resource allocation are adjusted. Students clarify improvement directions through personalized evaluation reports, achieving "evaluation promotes learning." Teachers improve teaching design based on evaluation data, achieving "evaluation promotes teaching," and ultimately forming a virtuous cycle of "evaluation — diagnosis — improvement — re-evaluation."

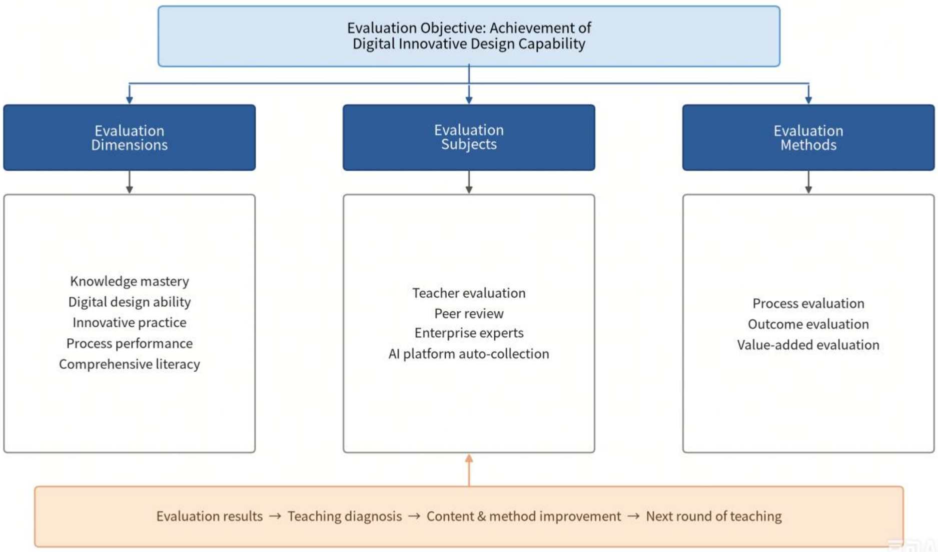

Fig. 3 Multi-dimensional evaluation system and feedback closed loop

IV. CONCLUSION

Facing the talent demand of intelligent manufacturing, the core of the teaching reform for digital innovative design in mechanical majors lies not in simply adding AI tools, but in taking capability cultivation as the main thread, deeply embedding artificial intelligence into the whole process of "content–implementation–evaluation," and realizing a systematic restructuring of teaching objectives, content, methods, platforms and evaluation. The five-in-one reform scheme proposed in this paper clarifies the reform content, four-stage implementation steps and three-dimensional multi-evaluation method, and has clear operability and testability. The scheme still needs to be tested by large-scale teaching practice. Follow-up work will rely on pilot courses to conduct controlled experiments, track the reliability and validity of evaluation data and the value-added changes in students' capabilities, and continuously optimize the scheme according to technological iteration and industrial needs.

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