IOSR Journal of Research & Method in Education (IOSR-JRME)
e-ISSN: 2320–7388, p- ISSN: 2320-737x Volume 15, Issue 6 Ser. 1 (Nov. – Dec. 2025), PP 50-54
www.iosrjournals.org

Reform of Teaching Methods for Mechanical Design Courses: Multi-chain Synergy and Hierarchical Exploration

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Abstract: *In response to the common problems existing in the current teaching of mechanical design courses, such as the disconnection between theory and practice, fragmented knowledge, and insufficient innovation and practical abilities of students, a "multi-chain synergy, hierarchical inquiry" teaching model is proposed. The multi-chains refer to the resource chain, problem chain, project chain, and evaluation chain, and synergy means the deep integration and mutual support among the four chains. Hierarchical inquiry means designing inquiry questions and tasks that follow the cognitive laws and progress from simple to complex and from easy to difficult. This model has been practiced in the "Mechanical Design" course of the Mechanical Engineering major at North China Electric Power University. Through the comparison of teaching data, student works, and questionnaires, it is shown that this method effectively enhances students' knowledge integration ability, engineering practice ability, innovative thinking, and comprehensive quality.*

Key words: *Multi-chain collaboration; Hierarchical exploration; Mechanical design; Teaching reform; Engineering education*

Date of Submission: 12-11-2025 Date of Acceptance: 29-11-2025

I.Introduction

1.1 Research Motivation

At present, a new round of technological revolution and industrial transformation is booming globally, and the Industry 4.0 era centered on artificial intelligence, digitalization and intelligence has already arrived[1]. To proactively respond to this change, higher education in China is vigorously promoting the construction of "New Engineering", with the core goal of cultivating future strategic talents who possess an interdisciplinary and composite knowledge structure, outstanding engineering practice ability, disruptive innovation thinking and profound patriotic feelings. This poses unprecedented challenges to the traditional engineering teaching model, especially for mechanical design courses closely linked to practice, demanding a profound paradigm shift from knowledge transmission to cultivation of ability and quality.

1.2 Teaching predicaments of mechanical design courses

Traditional teaching often presents knowledge such as theoretical mechanics, mechanical principles, mechanical design, and material processing in isolation by chapter, making it difficult for students to construct a complete knowledge chain: design requirements - mechanical analysis - structural realization - process manufacturing. There is a disconnect between course design and theoretical teaching, leaving students knowing "what" but not "why", and unable to transform formulas and principles into the ability to solve practical engineering problems.

The one-way indoctrination model of "teachers lecture, students listen; teachers set questions, students solve them" still dominates. Students lack the space for active exploration and in-depth thinking, and their status as the learning subject is absent, resulting in their critical thinking, problem-solving skills, and teamwork abilities not being effectively exercised.

The teaching objectives of courses often focus on the mastery of specific knowledge points, while there is a lack of clear and operational paths for cultivating comprehensive qualities and transferable abilities such as systematic thinking, innovative design, project management, and communication skills. The teaching content updates slowly, creating a gap with the latest industry technologies and the actual R&D processes of enterprises, making it difficult for graduates to quickly adapt to job requirements.

Therefore, exploring a new teaching method that can systematically integrate theory and practice, cultivate inquiry abilities in a stepwise manner, and deeply integrate industrial demands has become an urgent task to break through the teaching predicament of mechanical design courses and respond to the requirements of "new engineering" talent cultivation.

1.3 Research Status

The mainstream teaching models in China include the CDIO (Conceive-Design-Implement-Operate) model[2,3], which emphasizes the full life cycle of engineering education and serves as an important guiding concept. The PBL (Project-Based Learning) model[4,5] centers on real and complex problems or projects to drive student learning and has been proven to effectively enhance learning interest and comprehensive abilities. The OBE (Outcome-Based Education) model focuses on the final abilities students acquire to design the curriculum system in reverse. Many universities have actively introduced and localized these models in mechanical engineering education, implementing reforms such as project-driven teaching and curriculum integration design, achieving initial success and demonstrating the feasibility of student-centered and practice-oriented teaching reforms.

Most existing studies focus on reforms in a single aspect but fail to view knowledge, projects, abilities, and industries as an organic and interrelated ecosystem (i.e., multi-chain), lacking effective mechanisms to make them work in synergy. Although models like PBL are widely applied, the stepwise design of the exploration process is often arbitrary and does not strictly follow the progressive law from cognition to application and then to innovation. In summary, there is still room for deepening in the dimensions of systematic integration and scientific advancement in current research. This study, based on fully absorbing advanced educational concepts at home and abroad, aims to construct a more integrated and operational multi-chain synergy, stepwise exploration teaching model to address the aforementioned deficiencies.

II. The Multi-chain Synergy and Hierarchical Inquiry teaching model

To address the existing issues in current research, a teaching model called Multi-chain Synergy and Hierarchical Inquiry has been proposed. This model is based on advanced learning theories and achieves the deep integration and systematic improvement of knowledge, ability and quality by constructing and coordinating four main line chains and designing a scientific stepwise inquiry path.

2.1 Theoretical Basis

The construction of this model is based on constructivist learning theory[6,7] and inquiry-based learning theory[8,9]. Constructivism emphasizes that knowledge is not passively received but actively constructed by learners through interaction with the environment. This model completely discards the indoctrination teaching method and stresses the creation of real or near-real learning situations centered on the project practice chain. Students actively invoke and reorganize the knowledge theory chain by solving complex problems in hierarchical inquiry, thereby completing the construction of their personal knowledge system. The role of teachers shifts from knowledge providers to facilitators and guides of students' meaning construction. Inquiry-based learning theory holds that the learning process should simulate the research activities of scientists, starting from problems and obtaining knowledge and developing inquiry abilities through independent exploration, verification, and reflection. The design of the hierarchical inquiry path in this model is directly derived from this theory. It stimulates students' curiosity and cultivates their scientific thinking and habits of discovering, analyzing, and solving problems by setting a series of challenging and hierarchical inquiry tasks (from verification to design and then to innovation), thereby achieving deep learning.

2.2 Teaching Model

In response to the problems existing in mechanical design courses, the teaching model, which features multi-chain collaboration and hierarchical inquiry, has been proposed (Figure 1). This model includes the resource chain, problem chain, project chain and evaluation chain. It restructures the knowledge system with the guidance of a knowledge graph, builds a digital design resource platform, and forms a multi-dimensional and multi-state multi-level resource chain. It adopts a problem chain with increasing difficulty, analyzes multi-level engineering cases, and collaborates on projects with increasing complexity. It also switches students' roles to create a series of progressive multi-level learning activities, forming a four-method collaborative teaching approach. A self-developed student portrait analysis system is used to evaluate students' learning behaviors and construct a multi-dimensional quantitative evaluation chain.

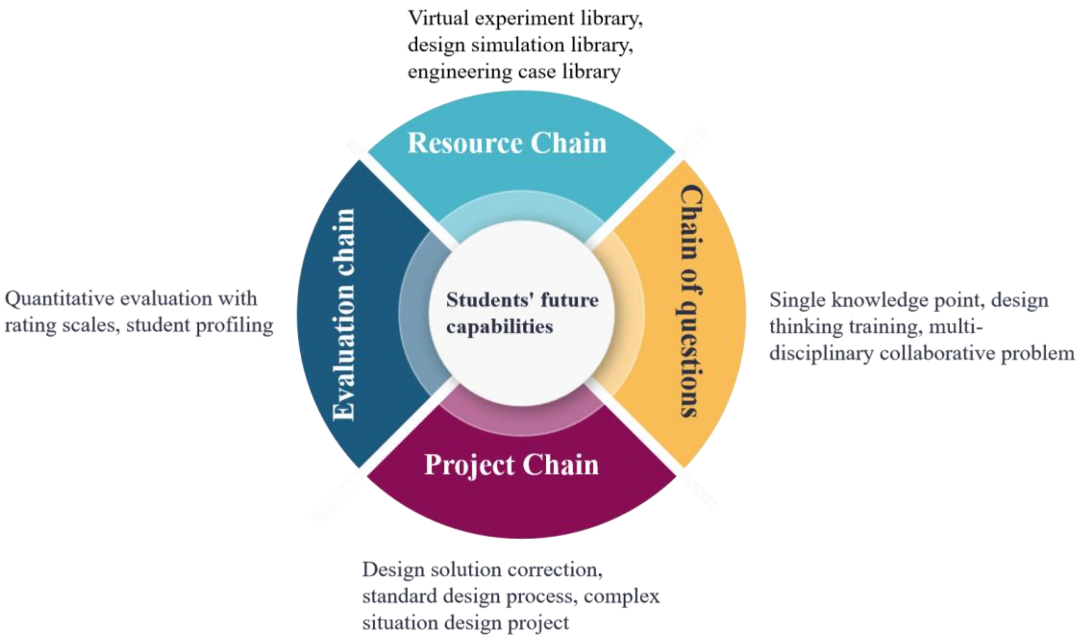

Figure 1 Teaching Model

The knowledge system of the course is reconstructed based on the IPD (Integrated Product Development) process of enterprise product development. A knowledge graph is constructed with the design main line of "working condition and force analysis - failure analysis - formulation of design criteria - size calculation - structural design" using failure analysis methods. The logical relationships between knowledge are sorted out, and a multi-state, multi-dimensional, and multi-level teaching resource chain is built in the self-built digital resource platform to solve the problem of scattered and fragmented knowledge points.

The cooperation and switching methods in the four-method collaborative teaching approach are used to train students' design capabilities through a project chain with increasing difficulty. Students are transformed into the role of designers and collaborate in teams to complete the projects in the project chain. Through learning design by doing design, students' independent design abilities are enhanced, achieving the transition from being able to design according to templates to being able to design in complex situations.

The exploration and analysis methods in the four-method collaborative teaching approach are used to create a problem chain with increasing difficulty based on the engineering case library, design simulation library, and virtual experiment library in the resource chain. Through the exploration of problems, students learn to analyze the design context of engineering cases and reduce the complexity of design tasks. Based on the design work appreciation library and critical thinking training library in the education chain, students learn to analyze design schemes in a critical thinking community composed of multiple subjects, enhancing their design critical thinking skills and meeting the requirements of new mechanical system design forms.

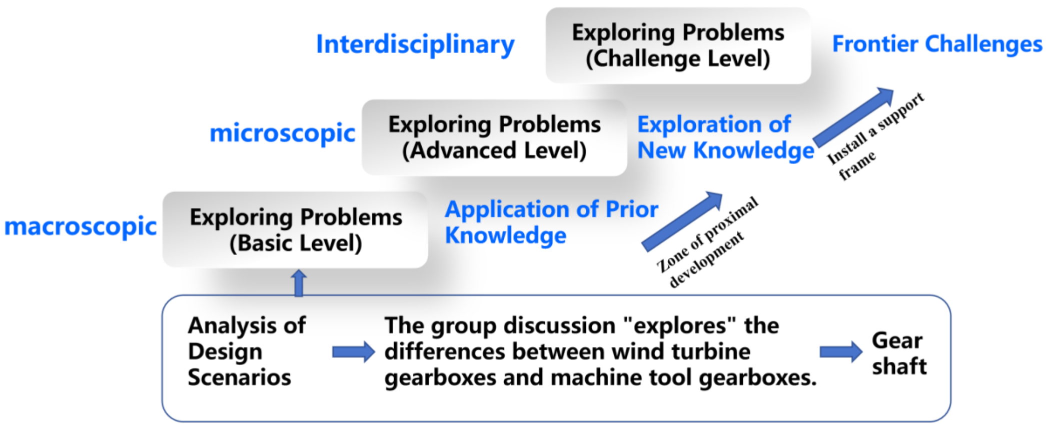

Figure 2 Problem exploration strategies

III. Teaching Case

Relying on the distinctive critical thinking resources constructed, the teaching methods are reformed from the dimensions of information analysis, independent thinking and decision-making that are necessary for the formation of innovative thinking. Before class, online resources are used for research and learning, with industrial cases from the field and the forefront of the discipline as the driving force, and challenging questions are set for students to conduct active exploration. During class, the problem chain teaching method is adopted, guiding students to conduct multi-mode interactions through group discussions and joint exploration with teachers, and enhancing critical thinking skills through multi-dimensional and diverse outputs. After class, a critical thinking community composed of enterprise experts, on-campus mentors and alumni is utilized, and critical thinking is formed in the process of writing analysis reports one by one.

(1) Before Class

The pre-class tasks include two items:

1) Analyze two student design works using the digital design resource platform

Assign research-based homework on the online learning platform, requiring students to watch two student design works on the digital design resource platform about the street lamp pole cleaning device, and conduct work appreciation. Try to analyze the advantages and disadvantages of the works (encourage students to analyze from multiple dimensions), and have online discussions.

2) Complete the project assignment (transmission system design)

Based on the actual project assignment topic given in the first week of this semester's course and the completed mechanical system requirements analysis and prime mover selection, complete the transmission system design. During the learning process of this chapter, take the project assignment as the driving force, and through the "learning by doing" and "doing while learning" approach, learn the design method of gear transmission, and then learn the general design method of mechanical parts.

(2) During Class

The four-method collaborative teaching method in the CECASE teaching model is adopted during class. This class mainly uses the collaboration task, exploration problem, and role transformation in the four-method collaboration. Start this class with the appreciation of two students' design works about the street lamp pole cleaning device, and conduct project learning and teaching with the project assignment of "design of the main transmission chain of a wind turbine installed in a certain place in Inner Mongolia". Students present their design plans and physical verification of the transmission process. Based on the students' design plans, the teacher introduces different scenarios, such as the transmission chain of a wind turbine installed on land in Hainan and the transmission chain of a wind turbine installed in the sea area of the Wenchang offshore oilfield in Hainan Province China. The teacher and students interactively discuss the impact of different scenarios on the design plan and subsequent structural design. Due to the different working conditions of the mechanical system in different scenarios, there is wind load fluctuation for wind turbine generators, which leads to the need to consider force analysis. Using the exploration problem method, the teacher and students interactively discuss the calculation of force direction, application point, and torque size in gear force analysis, and then introduce the knowledge of force analysis. Continue to explore the force analysis of spur cylindrical gears and helical cylindrical gears through interaction between the teacher and students, supplemented by physical objects. Through classroom exercises, students learn to judge the direction in force analysis and can use force analysis to initially explore the structural design of the shaft system.

(3) After Class

1) Complete the force analysis of gear transmission in the project assignment

2) Advanced after-class: If there are three gears on the intermediate shaft, how to handle it? The Challenging question is as following: considering the requirements for students' abilities in the construction of new engineering disciplines, challenging questions are set.

3) Industrial field problem exploration: When a wind turbine generator is running, the gearbox temperature alarm sounds, and noise and significant vibration are detected. Based on the provided monitoring data, determine whether it is related to excessive axial force?The Challenging question is as following: considering the requirements for students' abilities in the construction of new engineering disciplines, challenging questions are set.

4) Reverse thinking training: Is it necessary to use a gearbox in a wind turbine generator?The Challenging question is as following: considering the requirements for students' abilities in the construction of new engineering disciplines, challenging questions are set.

4.Teaching effectiveness

By comparing the performance of the experimental class with that of the control class, it can be found that students' academic performance has significantly improved, and their knowledge system has been systematically constructed. The students' grades have been notably enhanced before and after the reform. Taking the students of the 2019 grade as an example, the score rate of medium and high-level knowledge in this class is 12.4% higher than that of the parallel class. The data of students' design awards show that their design ability has been significantly enhanced.

Acknowledgement

This project is supported by the Hebei Province Higher Education Teaching Reform Research and Practice Project "Innovative Reform of 'Chain Synergy and Hierarchical Inquiry' Teaching Method for Mechanical Design Courses from the Perspective of New Engineering Talent Cultivation" (2023GJJG419) and the Hebei Province Postgraduate Education Teaching Reform Research Project "Research on the Cultivation Model of Critical Thinking Ability for Mechanical Postgraduates with 'Academic Foundation and People-oriented'" (YJG2024123).

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