

Under the perspective of industry-education integration, this study explores the innovative pathways for the training model of application-oriented talents in chemical engineering.

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Abstract: As the chemical industry undergoes a transition toward intrinsic safety, green manufacturing, and intelligent operations, the traditional discipline-oriented training model exhibits structural limitations against the backdrop of accelerating technological iteration. This study, grounded in the perspective of industry-education integration, elucidates the logical foundation of such integration from three dimensions: coupling mechanisms, competency structure, and model limitations. It introduces an organizational ecology perspective to analyze the organizational form innovation, resource interaction mechanisms, and operational evolution pathways of the integration community. Subsequently, guided by a competency-based orientation, it proposes a trinity of pathway innovations: the reconstruction of a modular and flexible curriculum system, the integrated cultivation of engineering thinking and innovative capability, and the implementation of full-cycle quality assurance and dynamic evaluation. The research indicates that the underlying logic of industry-education integration is rooted in the structural coupling between the industrial technology system and the disciplinary knowledge system. The construction of the integration community entails an evolutionary process from loose linkage to deep integration, and the competency-based innovation in training pathways can effectively respond to the chemical industry's inherent demand for interdisciplinary engineering talents.

Keywords: industry-education integration, application-oriented talents in chemical engineering, training model, organizational ecology, competency-based

Introduction

As a typical representative of the process industry, the chemical industry is undergoing a technological evolution shifting from unit operations to system integration and from empirical control to intelligent management and control. Such a transformation imposes higher demands on practitioners' engineering cognitive abilities, process optimization capabilities, safety ethics awareness, and green chemistry thinking. However, the traditional training model, which takes disciplinary logic as its main thread, features a curriculum system with a linear hierarchical structure. Its teaching content emphasizes theoretical deduction while weakening systematic integration training, and its evaluation methods struggle to effectively assess higher-order abilities such as engineering judgment and multi-objective optimization decision-making. Against the backdrop of industrial digital transformation, such a model exposes structural tensions including slow responsiveness in knowledge updating and a unidimensional approach to capability cultivation. This study starts with the coupling mechanism of industry-education integration, reconstructs the core competency framework, then constructs the operational mechanism of the integration community from the perspective of organizational ecology, and ultimately proposes a systematic cultivation pathway based on a competency-oriented approach.

1. The Logical Foundation of Industry-Education Integration and the Reconstruction of Elements in Chemical Engineering Talent Cultivation

1.1 The Coupling Mechanism and Value Dimensions of Industry-Education Integration

The underlying logic of industry-education integration in the chemical engineering field is rooted in the structural coupling between the industrial technology system and the disciplinary knowledge system. As a typical representative of the process industry, the chemical industry exhibits a technological evolution characterized by a transition from unit operations to system integration and from empirical control to intelligent management and control. This transition necessitates that the talent cultivation system break through the closure of traditional disciplinary boundaries. From the perspective of systems theory, the essence of industry-education integration lies in the transformation of the knowledge production model from a discipline-driven approach to a scenario-driven approach. Real-world scenarios in chemical production, such as process optimization, safety control, and environmental constraints, become the core arenas for knowledge reorganization and innovation, thereby enabling a deep intertwining of academic logic and engineering logic within the talent cultivation chain^[1].

The effective operation of the coupling mechanism depends on the establishment of a value consensus and the alignment of goal dimensions. In the chemical engineering field, the intersection of values between industry and education is reflected in their shared adherence to the generative principles of engineering competence. Educational institutions focus on the systematic construction of cognitive structures, while industrial entities emphasize the achievement of effectiveness in technical operations and problem-solving. This unification of value dimensions transforms industrial engineering standards, safety norms, and quality awareness into endogenous constraints within the talent cultivation process through mediating forms such as technology research and development platforms and process innovation projects, thereby forming an isomorphic relationship between knowledge transmission and technical inheritance at the value level.

1.2 Deconstruction of the Core Competencies of Application-Oriented Talents in Chemical Engineering

The core competencies of application-oriented talents in chemical engineering possess distinct engineering attributes and industry characteristics. Against the backdrop of the chemical industry's transformation toward intrinsic safety, green manufacturing, and intelligent operations, the core competencies of new-type chemical engineering talents can be deconstructed from four dimensions: engineering cognitive ability, which encompasses the systematic identification of chemical processes, the understanding of intrinsic correlations among process parameters, and the grasp of material and energy transformation mechanisms in unit operations; process optimization capability, which is reflected in systematic thinking regarding technical improvements to production processes, energy efficiency enhancement, and resource utilization efficiency improvement; safety ethics awareness, which includes the systematic identification of risks in chemical processes, the construction of emergency plans, and the internalized recognition of safety culture; and green chemistry thinking, which manifests as a full life-cycle environment-friendly philosophy from source reduction and process control to end-of-pipe treatment.

The four dimensions of competencies present an organic structure characterized by hierarchical progression and mutual permeation. Engineering cognitive ability constitutes the foundational layer of the competency system, determining the depth of an individual's understanding of complex chemical engineering systems. Process optimization capability and technical implementation capability form the application layer, supporting individuals in solving practical engineering problems. Safety ethics awareness and green chemistry thinking constitute the value layer, guiding individuals to balance the multiple objectives of efficiency, safety, and the environment in technical decision-making. This hierarchical structure reflects the compound and dynamic nature of the demands that the chemical engineering field places on talents. Individuals are required not only to possess a solid engineering foundation and operational skills but also to maintain the intrinsic motivation for sustained learning and adaptive development in an environment of rapid technological iteration.

1.3 Structural Limitations of the Traditional Training Model and the Imperative for Transformation

The traditional training model for application-oriented talents in chemical engineering exhibits

pronounced discipline-oriented characteristics in its organizational form. These are primarily manifested in a curriculum system organized around disciplinary logic rather than engineering logic, and in teaching content that emphasizes theoretical deduction of unit operations while weakening systematic integration training. From the perspective of knowledge transmission, the traditional model's linear hierarchical structure of "basic courses - specialized basic courses - specialized courses" offers advantages in knowledge comprehensiveness; however, it also reveals drawbacks of excessive rigidity and slow responsiveness when addressing the accelerating pace of technological iteration within the industry. A deeper issue lies in the traditional model's tendency to simplify chemical processes into idealized mathematical models, which obscures real-world constraints such as non-ideal factors in actual production, fluctuations in equipment characteristics, and variations in raw material quality. This results in the development of cognitive structures in learners that cannot be effectively transferred to complex engineering situations^[2].

The structural limitations of the traditional model are also reflected in the single-dimensional orientation of its evaluation system. The summative assessment, which primarily relies on course examinations, focuses on evaluating the ability to memorize knowledge and perform formulaic derivations, while it lacks effective assessment tools for higher-order abilities such as engineering judgment, fault diagnosis capability, and multi-objective optimization decision-making. This evaluation orientation reinforces learners' tendency toward examination-oriented approaches and weakens the space for developing engineering thinking and innovative capability. Faced with the demand for role capability reconstruction driven by the digital transformation of the chemical industry, the traditional training model exhibits a structural tension with industry development in terms of knowledge update speed, the dimensions of capability cultivation, and quality evaluation standards. This situation necessitates systematic reconstruction in areas such as the organizational form of talent cultivation, curriculum structure, and evaluation mechanisms.

2. The Construction Mechanism of the Industry-Education Integration Community from the Perspective of Organizational Ecology

2.1 Innovation in the Organizational Form of Integration Involving the Participation of Multiple Subjects

From the perspective of organizational ecology, the construction of the industry-education integration community in the chemical engineering field is first reflected in the profound restructuring of organizational forms among multiple subjects. In the traditional model, chemical engineering colleges and industrial organizations maintain a loose collaborative relationship, with significant differences between the two parties in terms of organizational boundaries, operational logic, and value orientations, thus occupying relatively independent ecological niches. The innovation in the organizational form of integration aims to break this structural separation and to construct symbiotic organizational units oriented toward the dual objectives of technological research and development and talent cultivation. Through the cross-embedding of organizational structures, this organizational form organically integrates resources from the industrial side, such as technology research and development centers, process laboratories, and pilot-scale platforms, with the teaching organizations and research institutions from the educational side, thereby forming an integrated carrier that combines the functions of teaching, research and development, and technical services.

The technical characteristics of the chemical industry impose specific requirements on the integrated organizational form. The continuous, systematic, and safety-sensitive nature of chemical processes determines that the construction of an integrated organization must fully consider the constraints imposed by the integrity of the process flow on talent cultivation. In contrast to discrete manufacturing industries, the transmission of technical knowledge and the cultivation of capabilities in the chemical engineering field rely more heavily on the understanding and operation of complete production systems. This requires the integrated organizational form to utilize actual process units or production equipment as carriers, thereby constructing an organizational environment capable of accommodating real production processes. This organizational design, guided by the principle of technological system integrity, enables the integrated unit to achieve a transition in functional positioning from a supportive teaching site to a platform that integrates technological development and capability generation.

2.2 Resource Interaction and Element Flow Mechanisms Guided by Integration

The core of the resource interaction mechanism under the guidance of integration lies in unblocking the channels for element flow between the chemical industry system and the education system, thereby achieving mutual empowerment of core resources such as knowledge, technology, equipment, and talents. The tacit nature of technical knowledge in the chemical engineering field is particularly prominent, as a large number of process know-how, fault diagnosis experiences, and optimization strategies cannot be effectively transmitted through textual forms alone. Instead, their internalization and transfer must rely on actual engineering scenarios and mentorship-based transmission. Targeting this characteristic, the resource interaction mechanism designs a knowledge transformation pathway based on real project carriers. This mechanism enables technical experts, process data, and operational experience from the industrial side to be transformed into cognitive resources that can be embedded into the teaching process. Simultaneously, it allows theoretical research findings and experimental data from the educational side to feed back into industrial technological improvement, thereby forming a closed-loop cycle between knowledge production and knowledge application^[3].

The operation of the element flow mechanism relies on structured institutional arrangements and carrier designs. From the dimension of material resources, chemical equipment and experimental devices are characterized by high investment intensity, strong specialization, and high maintenance costs. The element flow mechanism needs to address the cost allocation and usage right configuration of equipment resource sharing through contractual methods, clarifying the rights and obligations of each party regarding resource investment and benefit distribution. From the dimension of human resources, the flow of technical talents requires the establishment of a flexible mechanism of bidirectional embedding. This includes not only the participation of industrial technical experts in curriculum development and engineering guidance but also the involvement of faculty members from educational institutions in on-site production activities, engaging in technological problem-solving and process improvement. This bidirectional flow mechanism helps to break down human resource barriers between organizations, enabling the talent cultivation process to dynamically incorporate cutting-edge industrial technological elements while simultaneously allowing industrial organizations to continuously access the source of theoretical innovation.

2.3 The Operational Logic and Evolutionary Path of the Industry-Education Integration Community

The operational logic of the industry-education integration community is built upon the coordination and integration of the goal heterogeneity among multiple subjects. Chemical industry organizations pursue the enhancement of technological competitiveness and the realization of economic benefits, while the core concerns of educational institutions lie in the quality of talent cultivation and the level of disciplinary development. A natural tension exists between the two parties in terms of goal orientation. The effective operation of the community requires the construction of a coordination mechanism that accommodates multiple goals, enabling all parties to achieve value co-creation through integration. From the perspective of organizational behavior, the core of this coordination mechanism lies in establishing engineering capability generation as the common strategic fulcrum of the integration community. The industrial side gains high-quality technical talents with systems engineering capabilities through participation in talent cultivation, while the educational side achieves dynamic alignment between teaching content and industry demands by embedding itself in industrial scenarios. The two parties thus form a complementary interdependent relationship within the chain of capability generation.

From the perspective of the evolutionary path, the formation and development of the industry-education integration community exhibit phased characteristics, progressing from loose linkage to deep integration. In the initial stage, multiple subjects form a temporary collaborative network based on project-driven initiatives or resource complementarity, with each party engaging in limited cooperation while maintaining the integrity of its organizational boundaries. As the depth of collaboration increases and trust mechanisms are established, the community gradually enters the stage of structural integration. Organizational boundaries begin to blur, and the mutual exchange of personnel, resource sharing, and joint formulation of standards become normal operational features. In the advanced stage of evolution, the community may develop into an integrated carrier with independent legal entity status or a quasi-organizational form, achieving a high degree of synergy among talent cultivation standards, technology research and development directions, and industrial strategic needs. The technology-intensive characteristics of the chemical industry determine that the evolution of its integration community tends toward transitioning to an advanced-stage form, as only through deep

integration of organizational structures can the inherent demands of complex engineering talent cultivation for a systematic engineering environment be effectively met^[4].

3. Innovation in the Training Pathway for Chemical Engineering Talents Based on a Competency-Based Orientation

3.1 Modular and Flexible Reconstruction of the Curriculum System

The reconstruction of the curriculum system for application-oriented talents in chemical engineering needs to take the generative principles of competence as its logical starting point, break away from the traditional discipline-oriented approach to curriculum organization, and construct a modular architecture centered on engineering competence units. The process flow characteristics of the chemical industry determine that practitioners require a progressive competence structure, ranging from unit operation cognition to system integration optimization. Modular design reorganizes the curriculum content according to competence dimensions, forming functional units that cover basic process modules, process control modules, safety and environmental protection modules, and intelligent chemical engineering modules. Each module integrates the theoretical knowledge, technical principles, and engineering norms of relevant disciplines, enabling learners to form systematic cognition and operational capabilities corresponding to specific engineering fields upon completing the module, thereby achieving an effective mapping between knowledge elements and competence objectives.

The design of the flexible mechanism aims to enhance the curriculum system's responsiveness to technological iteration in the chemical industry. Faced with the continuous emergence of new materials, new processes, and new equipment, the flexible curriculum system constructs a hierarchical structure consisting of "core required modules, directional elective modules, and frontier dynamic modules," thereby reserving space for embedding emerging technological fields while ensuring the stability of the core knowledge system in chemical engineering. The flexible design of the curriculum schedule allows learners, after completing the foundational modules, to independently choose the learning paths and pace of subsequent modules according to their personal development directions and capability reserves, thus achieving a transition from standardized cultivation to personalized development pathways^[5].

3.2 The Integrated Cultivation Paradigm of Engineering Thinking and Innovative Capability

The integrated cultivation of engineering thinking and innovative capability requires the construction of a deep learning paradigm centered on complex engineering problems at the instructional level. Engineering problems in the chemical engineering field are characterized by multivariate coupling, complex constraints, and high decision-making risks. The core of the integrated cultivation paradigm lies in transforming unstructured problems from real engineering scenarios into teaching contexts, guiding learners to simultaneously cultivate the technical rationality of engineering thinking and the breakthrough nature of innovative capability in the process of problem-solving. The project-based learning sequence based on the entire chemical process flow forms a collection of engineering problems at varying levels of complexity, ranging from unit equipment operation optimization to section interlocking control, and from workshop production organization to plant system design. This enables learners to achieve a spiral elevation of their engineering cognitive structure through progressively advancing problem contexts.

The cultivation of innovative capability is embedded within the higher-order cognitive activities involved in the process of engineering problem-solving. Technological innovation in the chemical engineering field manifests as improvements to process routes, optimization of reaction conditions, enhancement of separation processes, or refinement of safety control strategies. In essence, it represents the reconstruction and transcendence of existing engineering knowledge. The integrated cultivation paradigm introduces open-ended engineering propositions, encouraging learners to explore multiple technical solutions under given constraints and to conduct solution comparison and optimization through multi-dimensional indicators such as techno-economic analysis, safety risk assessment, and environmental impact evaluation. This instructional arrangement enables learners to develop a complete cognitive chain of innovation — encompassing problem identification, solution conception, technical verification, and effect evaluation — in the process of completing engineering tasks, thereby achieving an organic unity between engineering thinking training and innovative capability cultivation.

3.3 The Full-Cycle Quality Assurance and Dynamic Evaluation Mechanism

The full-cycle quality assurance system requires extending the scope of quality monitoring from the endpoint of cultivation to the entire cultivation process, thereby constructing a complete closed loop covering the entry point of enrollment, the cultivation process, and the exit point of graduation. The quality characteristics of application-oriented talent cultivation in chemical engineering are reflected in three dimensions: knowledge acquisition, skill attainment, and competency formation. The generation of capabilities across these different dimensions follows its own time cycles and formation patterns. Addressing the specific characteristics of the chemical engineering discipline, the quality assurance system establishes phased observation nodes for competency achievement. It sets knowledge integration assessments during the foundational theoretical learning stage, skill proficiency evaluations during the unit operation training stage, and project completion assessments during the comprehensive engineering practice stage, thereby forming a staged, multi-dimensional layout for quality monitoring.

The core of the dynamic evaluation mechanism lies in the transition from summative assessment to developmental assessment, thereby constructing a new evaluation model based on the accumulation of competency evidence. The dynamic evaluation introduces multiple evaluation tools such as portfolio assessment, performance assessment, and peer assessment to systematically collect evidence of learners' performance in various engineering tasks, forming an individual profile that reflects the trajectory of competency development. In the chemical engineering field, this evaluation approach is particularly suitable for assessing higher-order competencies such as engineering judgment, safety risk identification capability, and multi-objective optimization decision-making capability, because the formation of these competencies requires observation and judgment through behavioral performance in real or simulated engineering contexts. The feedback mechanism of the evaluation results provides learners with diagnostic information regarding their competency development status in a timely manner, guiding them to adjust their learning strategies and directions of effort, thereby forming a virtuous cycle in which evaluation and learning reinforce each other.

Conclusion

From the perspective of industry-education integration, this study systematically explores the innovative pathways for the training model of application-oriented talents in chemical engineering. At the level of logical foundation, the study reveals that the essence of industry-education integration lies in the transformation of the knowledge production model from a discipline-driven approach to a scenario-driven approach. The intersection of values between industry and education is reflected in their shared adherence to the generative principles of engineering competence. The core competencies of application-oriented talents in chemical engineering should encompass four dimensions: engineering cognitive ability, process optimization capability, safety ethics awareness, and green chemistry thinking. The structural limitations of the traditional training model in terms of curriculum organization, knowledge presentation, and evaluation orientation necessitate systematic reconstruction. At the level of organizational ecology, the study proposes that the construction of the integration community requires breaking away from traditional loose collaborative relationships to form symbiotic organizational units oriented toward the dual objectives of technological research and development and talent cultivation. Through resource interaction mechanisms, the community achieves mutual empowerment of knowledge, technology, equipment, and talents, with its evolutionary path exhibiting phased characteristics progressing from loose linkage to structural integration and then to deep synergy. At the level of pathway innovation, the study constructs a competency-oriented trinity training model, namely the modular and flexible reconstruction of the curriculum system, the integrated cultivation paradigm of engineering thinking and innovative capability, and the full-cycle quality assurance and dynamic evaluation mechanism. Future research can further focus on the differentiated adaptation of integration models among different types of chemical engineering colleges and industrial organizations, explore quantitative evaluation methods for the operational performance of the integration community, and investigate the profound influencing mechanisms of intelligent technologies on the transformation of chemical engineering talent training models.

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