Vol. 5, No. 2 Education Research and Development April, 2026
第 5 卷第 2 期 教育研究与发展 2026 年 4 月

Teaching Strategies for “Industrial Control Network Course” in Petrochemical Universities via Competency Model and CDIO Integration

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Abstract: Considering the characteristics of talent cultivation in the Measurement and Control Technology and Instrumentation program, the various competencies outlined in the CREAVE model are adopted as educational objectives and guiding principles, while the CDIO engineering education concept is used as the cultivation pathway. By fully integrating these two approaches and taking into account the current teaching status of the Distributed Control System and Industrial Control Network course in our college, multiple teaching methods, such as goal-oriented problem-based teaching, case-based teaching, student group discussions, and team project practice, are systematically applied to the teaching reform and practice of this course. This approach aims to cultivate and exercise students' innovation ability, sense of responsibility, teamwork skills, and engineering professionalism, motivating them to becoming “high-quality engineering and technical talents who pursue excellence” as their goal for self-improvement. Through this curriculum model reform, the dual purpose of enhancing students' professional qualities and practical abilities is achieved.

Keywords: Competency Model; CDIO Engineering Education Concept; Teaching Model Reform; Emerging Engineering Education Construction; Process Control

DOI: 10.57237/j.edu.2026.02.002

1 The CREAVE Competency Model

In recent years, the continued implementation of the “Made in China 2025” national strategy, coupled with accelerated industrial upgrading, has highlighted the foundational role of electrical automation and measurement and control disciplines in the national economy. To meet the growing demand from intelligent manufacturing enterprises for highly skilled, interdisciplinary talent in these fields, universities must pursue sustained innovation in both the overarching framework and specific practices of talent cultivation. Informed by the national “Emerging Engineering Education” initiative and the ongoing curriculum development practices associated with the “Dual System” model at the college, two central pathways for reforming the teaching model have been identified: first, an internal focus on strengthening and reshaping students’ core competencies; second, an external emphasis on enhancing their ability to solve complex engineering problems.

1.1 From the “Onion Model” to the Awakening of Inner Drive

Tracing the theoretical origins, American social psychologist David McClelland first proposed the theory of competency in the 1960s and 1970s [1, 2]. This theory emphasizes that competency encompasses the underlying and enduring characteristics of an individual, such as motives, traits, self-concept, and social roles, which collectively determine whether one can achieve outstanding performance

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Received: 14 March 2026; Accepted: 20 April 2026; Published Online: 13 May 2026 http://www.educationrd.com

in their career [3, 4]. Later, American scholar Richard Boyatzis extended McClelland's work through more in-depth and broader applied research, introducing the well-known "Competency Onion Model" in the field of education [5]. As illustrated in Figure 1, this model reveals the layered structure of competency: at the core lie an individual's "personality" and "motives." Personality refers to one's stable patterns of response to the external environment and various stimuli, while motives are the internal drives that propel an individual toward specific goals.

Much like the layers of an onion, a person's personality and motives form the innermost core of their developmental potential. Radiating outward from this core are their attitudes and values, which shape the outermost layer—observable knowledge and professional skills. While knowledge and skills (the outer layer) are relatively easy to cultivate and assess, the inner layers (attitudes and motives) are far more difficult to evaluate and develop later in life. Yet it is precisely these inner qualities that determine whether a student can grow into an "outstanding engineer," making them the focal point of educational efforts.

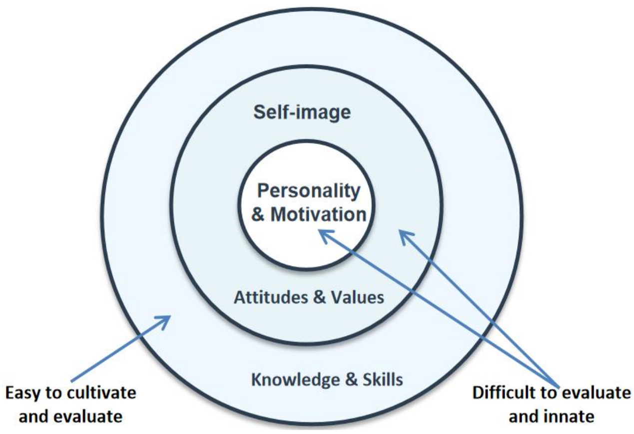

Figure 1 Onion Competency Model

1.2 The "CREAVE" Competency Model

Building on the pedagogical foundation discussed-above in Richard Boyatzis's "Competency Onion Model," and with reference to established competency frameworks in the literature [6], we have developed a tailored competency model for cultivating highly competent engineers in petrochemical universities. This model, encapsulated in the acronym "CREAVE," captures the core attributes essential for the petrochemical field and encompasses five key dimensions:

(1) C (Consecration): reflects the traditional spirit of dedication in the petrochemical industry, emphasizing commitment to frontline work, resilience in the face of hardship, and a diligent work ethic.

(2) R (Rule): represents the rigorous standards and regulatory frameworks inherent to high-risk petrochemical environments, highlighting legal compliance, safety awareness, and procedural discipline.

(3) E (Earnest & Environment): captures a dual focus—internally, it denotes personal qualities such as meticulousness, sincerity, and a collaborative mindset; externally, it embodies the industry's growing commitment to environmental sustainability, green manufacturing, and harmony with nature.

(4) A (Aspiration): signifies students' drive to excel in the field of automation, coupled with a broader ambition to contribute to national scientific and technological self-reliance.

(5) V (Value): encompasses both the professional ethics that engineers must uphold and the personal fulfillment gained through serving the nation and realizing one's potential.

This competency model aligns closely with the layered logic of the "Onion Model": it anchors itself in the inner dimensions of personality and motivation, while also giving full expression to the outer dimension of practical competence and innovation—qualities increasingly emphasized in contemporary science and engineering education. Moreover, the competencies embedded in this framework are highly consistent with the principles of the "Dual System" curriculum currently being promoted in higher education. Adopting this model as a guide for holistic competency development will significantly enhance the cultivation of outstanding engineers in petrochemical universities—engineers who are not only technically proficient but also possess strong professional integrity and adaptability.

2 Integration of CREAVE Competency Model with CDIO Engineering Education Model

The well-defined competency profile expected of engineering students is not innate but emerges from sustained interaction between intrinsic motivation and external factors. Crucially, this competency structure can be systematically cultivated and reshaped through well-designed educational and training approaches. In recent years, national initiatives, such as the "Excellent Engineer Education and Training Program," the development of "Emerging Engineering Education," and the "Dual System" curriculum reform at our college, have shared a common objective: to effectively integrate implicit character education with explicit technical training, thereby producing highly qualified engineering talents who possess both professional competence and moral integrity.

2.1 Introduction and Critical Review of the CDIO Model

CDIO—an internationally recognized framework for engineering education reform—was proposed in 2000 by a collaborative research team from leading institutions including the Massachusetts Institute of Technology (MIT) and the Royal Institute of Technology in Sweden, and the CDIO International Cooperation Organization was subsequently established in 2004 [7].

(1) Core Concept: CDIO stands for Conceive, Design, Implement, and Operate. It represents both an educational philosophy and an implementation framework organized around these four stages of the engineering lifecycle.

(2) Framework and Methodology: Directly inspired by the lifecycle of real-world engineering products or systems, the model uses the full trajectory—from initial concept through design, implementation, operation, and eventual decommissioning—as its organizing principle. This approach supports the development of a coherent, integrated curriculum that encourages students to actively engage in engineering learning through hands-on practice.

(3) Educational Objectives: The CDIO model places strong emphasis on cultivating comprehensive innovation capabilities, advocates coordinated development between engineering systems and their broader social contexts, and prioritizes hands-on engineering experience. Its syllabus categorizes engineering competencies into four dimensions: foundational technical knowledge, personal professional skills, interpersonal and teamwork abilities, and system-level engineering competence. These four dimensions align closely with our institutional goal of developing advanced application-oriented talents.

However, as an imported framework, CDIO requires contextual adaptation to local educational environments. Given its origins outside China, the model inherently lacks integration with the ideological and political education dimensions central to Chinese higher education. Moreover, by treating engineering competence development largely as an industrial "product/system" to be designed and implemented, the approach often appears mechanistic and offers limited attention to engineering ethics and humanistic concern.

2.2 The CREAVE-CDIO Integrated Model

In the current context of advancing "Emerging Engineering Education" and the "Excellent Engineer Education and Training Program," traditional engineering education faces persistent challenges: value guidance often remains disconnected from capability development, and humanistic literacy is frequently treated separately from engineering practice. As an internationally influential paradigm, CDIO offers a comprehensive structure for cultivating engineering capabilities; yet in localized implementation, it reveals certain limitations—insufficient integration of ideological and political content, underrepresentation of industry-specific cultural characteristics, and limited emphasis on humanistic dimensions. Meanwhile, the CREAVE competency model—grounded in Onion Model theory and deeply informed by the petrochemical industry context—provides a value-centered foundation for engineering education [8-10]. Through its logic of "internal-drive externalization," it connects underlying competencies to professional practice but lacks a clear operational pathway for translating abstract qualities into concrete engineering capabilities.

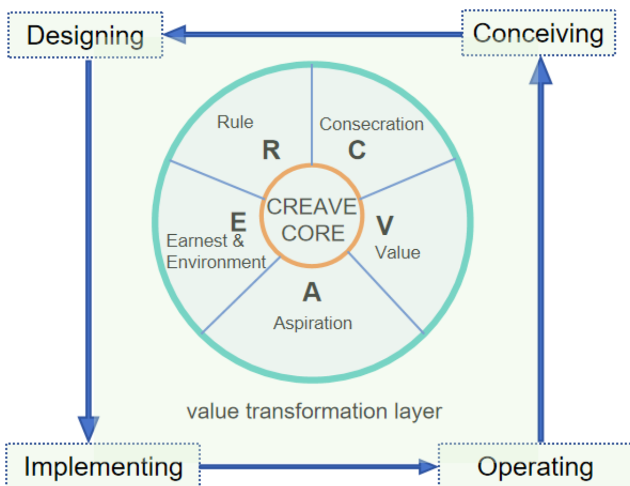

Figure 2 CREAVE-CDIO Integration Model

To address both the strengths and limitations of these approaches, we propose the CREAVE-CDIO integrated model, illustrated in Figure 2. This framework adopts a three-layer architecture — “value core, transformation intermediary, and practice outer ring” — enabling the integrated development from competency potential to engineering capability. It offers a concrete and actionable pathway for cultivating outstanding engineers in industry-focused universities who embody both technical excellence and strong professional character.

The CREAVE-CDIO integrated model features a three-layer progressive structure and operates through bidirectional empowerment. At its core lies the five-dimensional CREAVE kernel, which embodies the foundational value orientation for cultivating engineers. These five dimensions function as an integrated whole, providing value guidance and building an ideological foundation. Together, they constitute the intrinsic motivational layer—difficult to assess yet fundamentally determinative—corresponding to the core competencies in the Onion Model. This inner layer shapes students' attitudinal choices and value judgments throughout their engineering practice.

The intermediary layer is responsible for competency transformation and contextual empowerment, representing the innovative core of the model. It undertakes the critical mission of infusing technical rigor with humanistic sensitivity and embedding soft qualities into hard skills. Within this layer, a competency empowerment mechanism translates each CREAVE dimension into observable and assessable behavioral indicators. For instance, Consecration is reflected in accountability measures during project execution, while Rule is operationalized through compliance with design specifications, thereby converting abstract values into concrete behavioral norms for engineering practice. By embedding humanistic reflection nodes throughout the CDIO process—such as integrating technical ethics reviews during the Conceiving stage, incorporating user experience considerations during Designing, emphasizing collaborative engagement during Implementing, and assessing social impact during Operating—the model achieves a seamless integration of humanistic care with technical capability development. Additionally, an ethical review mechanism grounded in R (Rule) and V (Value) is established to ensure that technical solutions are not only feasible but also ethically sound, cultivating in students an engineering conscience characterized by reverence for standards and adherence to ethical boundaries. This intermediary layer effectively addresses the structural limitations of traditional CDIO in ideological-political education and humanistic cultivation, transforming value guidance from passive indoctrination into immersive experience, and from external imposition into internal conviction.

The outer ring comprises the CDIO four-stage closed loop, serving as the practical pathway through which competencies are externalized. Through capability building and hands-on application, this layer translates the CREAVE kernel into actionable engineering capabilities. During the Conceiving stage, driven by Aspiration, students develop the ability to identify industry challenges and define complex engineering problems through objective- and problem-oriented instruction. For example, students are guided to conceptualize smart factory solutions in response to the digital transformation needs of the petrochemical industry. In the Designing stage, informed by Rule (discipline) and Earnest (rigor), students receive training in system integration and multi-objective trade-offs, with emphasis on standards compliance, safety and environmental considerations, and ergonomic coordination. During the Implementing stage, grounded in the spirit of Consecration, students engage in intensive hands-on training through the integration of teaching, learning, and doing—including configuration programming, hardware wiring, and system debugging—thereby cultivating a craftsmanship ethos centered on excellence. In the Operating stage, guided by Value, attention is directed toward full-lifecycle operation and maintenance, as well as social benefit assessment, fostering awareness of continuous system optimization and social responsibility. These four stages form a spiraling, ascending closed loop; with each cycle, the infusion of CREAVE competencies enhances both the level and the scope of engineering practice.

Within the innovative framework of the CREAVE-CDIO integrated model—which merges the CREAVE competency framework with the CDIO engineering education paradigm—we offer a novel and practically implementable solution for cultivating high-quality engineering talents. Such graduates are distinguished by a solid ideological-political foundation, a well-structured and individualized competency profile, and a robust combination of engineering excellence and innovative capacity.

3 Strategies and Exploration of Teaching Models for Industrial Control Networks

The "Industrial Control Networks" course is a quintessential interdisciplinary professional course, primarily encompassing two core components: Distributed Control Systems (DCS) and Industrial Control Network Technology (course titles may vary slightly across universities). Its fundamental mission is to address the challenges in achieving reliable digital communication among massive field devices—such as intelligent instruments, controllers, and actuators—and to enable the construction of large-scale remote control systems. This course represents the deep integration and advancement of cutting-edge technologies, including process control, automation instrumentation, computer network communication, and control system software engineering. Within the petroleum and petrochemical industry—a lifeline of the national economy—industrial control network technology is extensively applied across the entire industrial chain, from upstream exploration and production to downstream refining and processing. Currently, universities in China that specialize in petrochemical engineering have widely adopted such courses to meet the demands of industrial upgrading. However, due to the course's extensive and rapidly evolving knowledge base, numerous challenges have emerged in teaching practice [11, 12].

3.1 Current Teaching Status and Existing Problems

(1) Mismatch Between Breadth of Content and Limited Class Hours

Surveys of domestic universities show that many institutions allocate only 32 credit hours to this rigorous course, with even those emphasizing the subject rarely exceeding 48 hours. Given the breadth of the knowledge system, instructors can only cover topics superficially within such constrained time, leaving students to resort to rote memorization. The severe compression of class hours leaves no room for in-depth interactive activities that could enhance students' comprehensive professional competencies.

(2) Mismatch Between Traditional Teaching Methods and Complex Content

Most courses still rely on conventional "cramming" teaching methods and monotonous multimedia PowerPoint presentations. Such dry approaches fail to help students truly grasp the substantive content of industrial control networks—a complex technical system spanning from the OSI seven-layer model to underlying physical characteristics. Students often find themselves "seeing the trees but not the forest", either skimming concepts or getting bogged down in trivial details without establishing a system-level cognitive framework [13].

(3) Mismatch Between Outdated Textbooks and Frontier Technology

Driven by rapid advances in semiconductor, artificial intelligence, and Internet of Things (IoT) technologies, industrial control networks are evolving at a dizzying pace. Many disruptive innovations have long been deployed at scale in industrial settings—such as digital oilfield construction, oil and gas production IoT, and smart factories. In contrast, existing textbooks contain outdated content with significant generational gaps. Teaching materials that closely track the latest technologies and are specifically oriented toward real-world petrochemical industry scenarios remain extremely scarce.

(4) Mismatch Between High Engineering Requirements and Weak Experimental Components

Due to inadequate theoretical class hours, experimental components are further compressed. Even worse, some universities, constrained by expensive hardware and limited facilities, cannot offer meaningful comprehensive practical training. Practical courses degenerate into "observation classes" where instructors demonstrate software from the podium, depriving students of valuable hands-on opportunities for wiring, configuration, and debugging. Consequently, the cultivation of engineering practice and innovation capabilities remains ineffective.

(5) Mismatch Between Vibrant Industry Status and Students' Entrenched Perceptions

Under long-standing stereotypes, many students mistakenly regard the petroleum industry as a "sunset industry". They believe that working in petrochemical enterprises involves high danger, dirtiness, and exhaustion, with some even explicitly stating they will not engage in related work after graduation. This serious cognitive bias undermines students' motivation to learn. However, with modern automation technology, working environments have undergone transformative changes: production areas now feature complete facilities, plants boast garden-like surroundings, and central control rooms are high-tech spaces—far removed from traditional harsh conditions.

These problems not only directly hinder the cultivation of students' professional competencies but also create a vicious cycle. Currently, the industry's demand structure for compound automation talents has profoundly shifted, with an extreme shortage of versatile talents who possess both solid ideological qualities and the ability to independently construct large-scale industrial control network systems. Therefore, the course urgently requires a fundamental reconstruction of its teaching philosophy. Introducing the CREAVE-CDIO integrated model for precise teaching reform offers a highly effective solution [14, 15].

3.2 Practical Teaching Strategies and Exploration Under the CREAVE-CDIO Integrated Model

Based on the above pain points, we comprehensively integrate the CREAVE competency model with CDIO engineering education, focusing on the following four strategic dimensions to conduct a series of fruitful teaching model explorations.

Strategy 1: Deeply Excavating Industry Genes, Strengthening Curriculum Ideological and Political Education, and Reshaping Students' Professional Beliefs (Corresponding to C, R, A, V elements in CREAVE)

The primary task of education is "soul-forging". During the course introduction phase, we do not merely teach dry network technologies but affectionately introduce the magnificent development history of China's petroleum and chemical industry and its role as the stabilizer of national security and people's livelihood.

(1) Historical Heritage

We share with students China's arduous journey from being an "oil-poor country" in the early days of the People's Republic, to the self-reliant discovery of the Daqing Oilfield, to the comprehensive rise of the modern petrochemical industry, and finally to today's confident march into overseas markets to develop international oilfields.

(2) Spiritual Edification

Through these true industry epics, combined with in-depth explanations of the irreplaceable importance of the petrochemical industry, we greatly stimulate students' patriotic enthusiasm and national pride, guiding them to bind their personal destiny with national needs and establish lofty goals of dedicating themselves to the petrochemical industry.

(3) Contemporary Resonance

We vividly demonstrate the journey of China's industrial control network technology from once being impoverished and constrained by others to now keeping pace with world frontier trends. Particularly by integrating recent "chokepoint" reality cases such as the Huawei chip embargo incident, we strongly stimulate students' patriotism, crisis awareness, and burning desire to study for the rise of China.

(4) Work Style Construction

We naturally integrate the world-renowned "Iron Man Spirit" of the Daqing Oilfield and the petrochemical industry's unique "Three Honesties and Four Strictnesses"—being honest people, speaking honest words, doing honest deeds; and strict requirements, strict organization, strict attitude, strict discipline—into the classroom. This edifies students to have lofty aspirations while remaining grounded and dedicated to their work, comprehensively consolidating their ideological and political literacy (embodiment of V and C).

Strategy 2: Keeping Pace with the Times, Dynamically Updating Content, and Maintaining the Vitality and Practicality of the Knowledge System (Corresponding to engineering system-level cognition cultivation in CDIO)

Given the lag of textbook content, instructors must become "living water" of knowledge. Throughout the teaching process, we require the teaching and research team to maintain keen sensitivity, continuously sorting out and summarizing major latest achievements and frontier evolution directions in the field of industrial control networks for students.

(1) Introducing Frontier Technologies

Based on traditional fieldbus, we resolutely added emerging content including Industrial Control Wireless Networks (Industrial Internet of Things, IIoT), modern industrial network architectures based on 5G ultra-low latency communication, and critically important industrial control network system information security defense.

(2) Connecting to Real Scenarios

We abandon empty theoretical preaching and directly use the authentic scheme design of the "Oil and Gas Production IoT System (A11)" currently being promoted on a large scale in China as teaching materials. We provide detailed analysis to students on how overall schemes for large-scale industrial control networks are designed, how multiple complex network communication methods (such as fiber optic ring networks, LoRa, ZigBee, etc.) are organically integrated, and what the latest practical technologies and application implementations for underlying security prevention in industrial internet systems are. This "down-to-earth" frontier teaching allows students to truly perceive the great practical value of their learning, greatly enhancing their internal motivation.

Strategy 3: Implementing Goal and Problem-Driven Teaching and Case-Based Instruction to Stimulate Engineering Innovation Inspiration (Corresponding to E in CREAVE and C-D stages in CDIO)

The classroom should not be a teacher's one-man show. In classroom teaching, we attach great importance to deep connections between theory and engineering practice, vigorously highlighting petrochemical industry characteristics, and committing to ignite students' enthusiasm for active thinking and exploration.

(1) Creating Real Dilemmas

We understand that relying solely on descriptive explanations and textbook lectures is both abstract and sleep-inducing. To break the deadlock, we carefully select a comprehensive control engineering project of an actual operating "joint station" in a large domestic oilfield as the core classroom case for dissection and demonstration.

(2) Panoramic Discussion

Centering on this massive and complex case, we guide students to think like real engineers. From the preliminary selection and design basis of the DCS distributed control system, the physical space arrangement of field control stations and central control operator stations, to the rational selection of system trunk communication methods and other key engineering dimensions, we pose questions, organize and vigorously encourage students to conduct group discussions and speak actively.

(3) Verification and Epiphany

After students have fully collided ideas, teachers then combine the actual practices and design considerations of engineers on the project site for in-depth comments and explanations. This process of "confusion-exploration- epiphany" gives students a strong sense of sudden clarity and achievement, greatly enhancing their innovative ability to solve unknown problems imperceptibly.

(4) Cross-Disciplinary Systems Thinking

Industrial control networks are never isolated; they are an important system in petrochemical engineering. In actual engineering, they have intricate interfaces with power supply systems, civil structures, drainage networks, and core process flows, and must strictly follow various national and industry standards (manifesting the R competency). Therefore, we deliberately set up complex systemic obstacles in class, give minimal hints, and guide students to provide global solutions like project chief engineers, fully mobilizing their high-order thinking.

For example: We ask guiding questions: "How can weak signals from instruments and actuators in explosion-proof areas be reliably transmitted over long distances to main control cards in field control stations? How should power supply issues for massive numbers of instruments be resolved on drawings?" After students discuss and give preliminary answers, we immediately throw out the real-world pain point of "high cost and susceptibility to interference of massive analog signal cable laying," thereby naturally and convincingly leading to the background and core advantages of Fieldbus systems. Through this high-density "problem-driven + scenario immersion" model, we not only unprecedentedly enhance students' classroom participation and immersion but also temper their practical qualities for responding to real complex engineering.

Strategy 4: Practicing the CDIO Full-Cycle Concept and Building an Integrated Teaching-Learning-Doing Practical Platform (Corresponding to I-O stages of CDIO and teamwork capabilities)

The essence of engineering education lies in "doing." In the teaching implementation process, addressing the objective shortcoming of severely limited traditional experimental class hours, we scientifically reconstruct the limited practical teaching components into two complementary and progressive parts: virtual simulation experiments and laboratory physical project research.

(1) Virtual Simulation (Conceiving and Designing Stages)

Students are mandatorily required to proficiently use mainstream industrial configuration software (such as WinCC, InTouch, etc.). In the virtual environment, students independently complete the establishment of engineering databases, complex configuration logic writing, development and debugging of underlying controller (PLC) control programs, and aesthetic and functional production of human-machine interaction (HMI) operation screens, thereby closed-loop verifying the correctness of their logical control requirements.

(2) Physical Project Research (Implementing and Operating Stages)

In advanced laboratory practice, we completely move beyond step-by-step verification experiments. By fully integrating and utilizing existing industrial-grade DCS systems and various fieldbus experimental platforms in the laboratory, we guide students in the research and implementation of real-world projects entirely in CDIO project operation mode. Students, working in teams, must undergo the complete engineering lifecycle experience from project conception and initiation (C), network topology drawing design (D), hardware wiring and software deployment implementation (I), to system integration debugging and troubleshooting operation (O).

4 Conclusion

Due to the openness of the CDIO engineering education system, it can be appropriately adopted and integrated according to different disciplines or even specific course requirements, thereby leveraging the positive role of CDIO in student engineering education. The teaching model reform for the “Industrial Control Networks” course in petrochemical universities, based on the integration of the “CREAVE” competency model with CDIO proposed in this paper, holds positive significance. In this process, the focus is not merely on teaching students a specific knowledge point or solving a particular problem to acquire knowledge; rather, it lies in enabling students to develop correct ideological and political literacy while fostering the determination to master the course content, and to learn how to identify, analyze, and solve problems—thereby acquiring the corresponding knowledge and capabilities. This integrated teaching model also emphasizes the cultivation and evaluation of humanistic qualities, including positive campus culture, environmental awareness, and harmonious development. Only in this way can students' ideological and political qualities, engineering practice abilities, and innovative competencies be comprehensively enhanced.

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