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Article

Teaching Reform of Chemical Safety Engineering Course Based on Safety Engineering Specialization

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Abstract: The chemical sector is undergoing rapid transformation, evolving to be more intelligent and environmentally sustainable. The conventional safety engineering education model is inadequate for addressing emerging threats. The existing Chemical Safety Engineering course faces fundamental issues, including antiquated content, rigid methodologies, and disjointed resources. To address these, this study proposes a novel four-pronged reform framework that reconstructs objectives, refreshes material, optimises technology use, and enhances assessment. This framework reconstructs objectives, refreshes material, optimises technology use, and enhances assessment. It achieves this by integrating a dynamic knowledge repository, virtual reality instructional situations, and a multi-faceted assessment framework. This establishes a "risk-predictive" approach to talent development. The paper provides theoretical backing and practical measures to transform chemical safety education for the modern day. This possesses significant scholarly merit and potential for industrial application.

Keywords: Chemical safety engineering, Teaching reform, Risk anticipation, Competency evaluation

1. Introduction

Under the background of the global chemical industry's transformation to greening and intelligence, traditional chemical safety education is facing serious challenges: on the one hand, the industrialized application of emerging technologies such as hydrogen storage and carbon capture has given rise to new types of risks (Pasman, 2020), but the existing teaching materials are still based on the core of the traditional unit operations such as distillation towers, reactors, and so on; on the other hand, the competence requirements of enterprises for safety engineers have been upgraded from "accident response" upgraded to "risk prediction-decision-making-prevention" whole chain ability, while college teaching still relies on paper HAZOP analysis, students lack of intuitive cognition of dynamic risk. Nonetheless, contemporary Chemical Safety Engineering (CSE) curricula in colleges exhibit three primary issues:

(1) There exists a disconnect between the supply of knowledge and industry demand, as educational materials are outdated in relation to international chemical safety technology standards, such as API RP 752/753 Process Safety Guidelines, and fail to address emerging risks, including the toxicity of nanomaterials and biochemical pollution (Allen, 2016).

(2) Teaching methodologies do not align with students' learning requirements: educators predominantly employ lectures, although it is challenging for students to comprehend the dynamics of risk variation and propagation, such as domino effects, when they only examine static scenarios.

(3) There exists a dichotomy between technological tools and educational contexts: while technologies like virtual simulations and digital twins are extensively utilised in industry, pedagogy continues to depend on two-dimensional flowcharts and paper checklists, hindering the creation of an immersive learning experience.

Chemical safety engineering is a professional basic course in safety engineering, which centers on chemical process safety issues, systematically introduces the basic theory and technical methods of chemical safety engineering, including hazardous chemical safety, fire and explosion prevention, chemical process and process heat safety, chemical device safety, corrosion and corrosion prevention, occupational hazards prevention and control technology, chemical safety evaluation, simulation and analysis of the consequences of chemical accidents and chemical safety management. The core objective of the program is to train professionals who can predict and manage chemical process risks.

Therefore, in view of the existing problems of chemical safety education, this paper puts forward the reform exploration for the education of chemical safety engineering course in response to the core demand of "cross-fertilization and practical innovation" of new engineering education, which is of double value. On the theoretical level, through reconstructing the course content framework of "technology-management-ethics", we can promote the paradigm shift of safety engineering education from "accident-responsive" to "risk-foreseeing"; on the practical level, we can integrate virtual reality, knowledge mapping, and other knowledge technologies into the course. At the practical level, we integrate emerging technologies such as virtual reality and knowledge mapping to build a "virtual-reality integration" chemical safety teaching scenario, providing students with a decision-making training environment close to real working conditions, and helping to solve the shortage of "technical but not good management" talents faced by enterprises.

This study employs a systematic reform of "content reconstruction - technology empowerment - evaluation innovation" to effectively cultivate "Safety 4.0" professionals in the "Chemical Safety Engineering" course, aligning with industrial transformation needs (Gajek, 2022; Velichko, 2025). The specific implementation pathway is illustrated in Fig. 1, Table 1 provides a summary of the solutions.

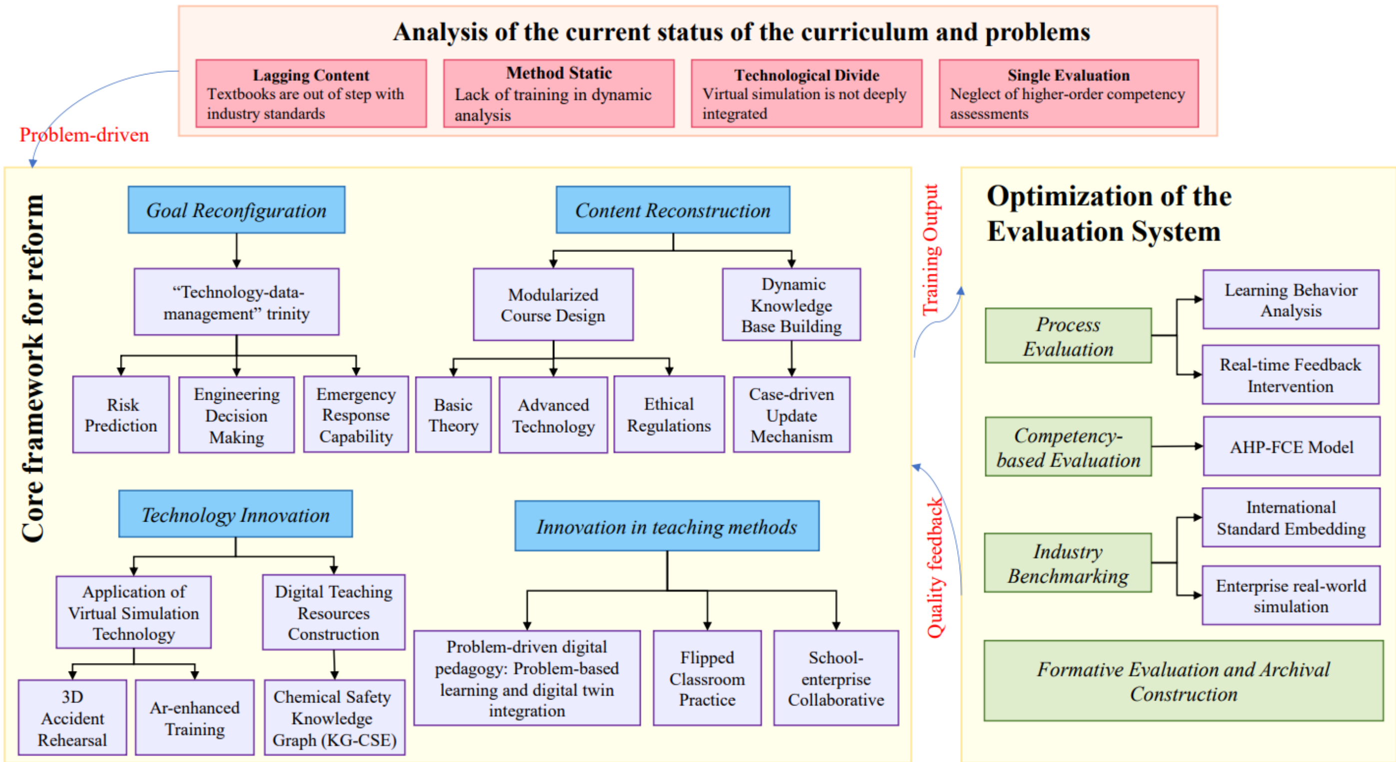

Fig. 1. Specific implementation path of teaching reform.

Table 1. Solution summary.

Problem Type (Section 2)	Solution (Sections 3–5)	Expected Results
Emerging risks are not adequately covered	A dynamic knowledge base updates cases in real-time	Emerging risk scenarios are stored
Static teaching lacks dynamic risk simulation	3D accident deduction system	40% faster response to student emergencies
Evaluations are disconnected from industry certifications	The CCPS capability model is embedded in the AHP-FCE assessment	Students receive pre-certification credits

2. Analysis of the Current Status of the Curriculum and Problems

2.1. Content Dimension: Knowledge System Lag and Fragmentation

The existing educational resources emphasise the safety of conventional chemical unit operations, including distillation towers and reactors, while inadequately addressing risk prevention and control in emerging energy chemical sectors, such as the safety measures for hydrogen production via water electrolysis and the insufficient focus on risk management associated with carbon neutralisation technologies, particularly the hazards of CO_2 pipeline transportation leaks.

An absence of integrated knowledge persists in current curricula. Given that chemical safety issues are intricate and require insights from various disciplines, such as safety engineering, data science, and environmental toxicology, the existing course content remains confined to a single discipline, failing to establish a hazard interrelationship analysis framework (Yi, 2025). The case base is outdated, mostly concentrating on historical incidents from the 20th century, such as the Bhopal gas leak and the Chernobyl nuclear disaster, while lacking comprehensive examination of contemporary events in the digital age, such as explosions resulting from DCS system miscommunication.

2.2. Methodological Dimensions: Static Teaching Models and Scenario Fragmentation

Inadequate utilisation of technical tools: HAZOP analysis software and leakage diffusion simulation tools are prevalent in the industry; however, instruction remains focused on manually constructing risk matrices, resulting in students missing the opportunity to engage with professional tools for dynamic risk quantitative analysis.

Practical training is deficient in authentic simulations; conventional techniques employ physical models or two-dimensional flowcharts. Due to the inability to replicate serious crises such as pressurised pipe bursts or chain explosions, pupils frequently struggle to visualise intricate disaster scenarios and respond promptly.

The collaboration between schools and enterprises is superficial; enterprise involvement is primarily restricted to lectures or site visits, and a comprehensive cooperation framework encompassing “case co-editing, scene co-construction, and teacher training” has yet to be established. For instance, the intelligent inspection systems commonly utilised by chemical companies have not been integrated into the practical components of the curriculum.

2.3. Evaluation Dimensions: Competency-Based Bias and Lack of Feedback

The present assessment employs solely one method: closed-book examinations. These assessments emphasise rote memorisation while neglecting advanced competencies such as risk prediction and resource coordination.

The absence of process feedback results in insufficient dynamic monitoring of students’ learning behaviours, including the documentation of operational pathways in virtual training. This deficiency hinders the identification of competency gaps through data-driven approaches, such as blind spots in risk assessment and flaws in decision-making logic, ultimately providing no foundation for enhancing teaching methods.

The decoupling of industry standards: the evaluation metrics are misaligned with the international chemical safety competence certification framework, such as the CCPS chemical process safety professional certification, and there is an absence of validation regarding the development of the enterprise’s core competencies, including the qualification of HAZOP chairman.

3. Core Framework of Pedagogical Reform

3.1. Goal Reconfiguration: Security Resilience-Oriented Capability System

To meet the needs of Industry 4.0, an interdisciplinary talent development framework that integrates technical competence, data literacy and ethical responsibility needs to be systematically constructed. Specifically, the framework focuses on developing three core competencies: (a) risk prediction using digital twins and AI-driven anomaly detection; (b) engineering decision-making based on multi-objective optimization with safety-cost-efficiency tradeoffs; and (c) emergency response planning through immersive simulation training.

3.2. Content Reconstruction Strategies: Modularization and Dynamic Knowledge Systems

3.2.1. Modularized Course Design: Solving Knowledge Fragmentation

Classical methodologies: comprehensive elucidation of the principles of HAZOP and LOPA. This encompasses elucidating their concepts and delineating step-by-step procedures. We adhere strictly to IEC 61882 standards to enhance the rigour of the analysis framework.

The reinforcement of engineering ethics is the organic integration of responsible care standards and process safety culture theory into the curriculum, so successfully augmenting students' awareness of engineering ethics.

Intelligent risk monitoring involves the systematic instruction of AI monitoring technologies for chemical processes, including LSTM-based anomaly detection systems, and the utilisation of digital twin technology for leakage simulation (Lee, 2019).

New energy safety: thoroughly address the safety of hydrogen energy storage and transportation, including the fatigue failure mechanisms of composite hydrogen storage cylinders and the risk management of carbon capture and storage systems.

International regulatory benchmarking: comprehensive examination of the EU SEVESO III directive and the US OSHA PSM standard, among others, to enhance students' understanding of worldwide compliance.

Case study on ethical conflict: develop intricate designs of standard ethical dilemma scenarios, such as "Cost Compression and Safety Investment Conflict" to enhance students' decision-making and evaluative skills in difficult settings.

3.2.2. Dynamic Knowledge Base Building

Case-driven update mechanism: integrate global major accident databases, such as CSB accident reports and China's Ministry of Emergency Management (MEM) case database, and use a spatio-temporal annotation system to achieve multi-dimensional case retrieval functions. Develop a collaborative update platform that invites enterprise experts to supplement information in real time on emerging risk scenarios, such as how to handle lithium battery leaks during emergencies.

3.3. Technology Innovation Path: Digital Empowerment of Virtual and Real Integration

3.3.1. Application of Virtual Simulation Technology

A 3D accident rehearsal system is constructed using the Unity engine to simulate scenarios such as reactor explosions, employing computational fluid dynamics to visualize leakage dispersion in real time. This system simultaneously facilitates multi-role collaborative rehearsals, encompassing operators, safety engineers, emergency commanders, and other roles, to enhance teamwork and resource coordination.

Augmented reality-enhanced training system: utilising Microsoft HoloLens and other devices, it facilitates perspective-based instruction on equipment structure, including the disassembly and visualisation of internal components of safety valves. Coupled with the Fault Tree Analysis (FTA) tool, it enables real-time diagnosis of virtual equipment anomalies.

3.3.2. Digital Teaching Resources Construction

The Chemical Safety Knowledge Graph (KG-CSE) is developed using the Neo4j graph database, linking the three essential components of "risk source-causal mechanism-prevention and control measures". An adaptive learning suggestion method is presented, necessitating the precise delivery of tailored learning resources based on students' deficiencies in abilities, encompassing micro-lesson videos, standard literature, and other materials.

4. Innovation in Teaching Methods

4.1. Problem-Driven Digital Pedagogy: Problem-Based Learning and Digital Twin Integration

Problem-oriented learning is empowered by digital twin technology, and a closed loop of "problem definition-virtual deduction-iterative optimization" is constructed (ZHOU, 2021):

Multi-constraint scenario design: Build high-risk operation scenarios on the digital twin platform, such as process optimization in confined spaces. Real-time decision-making training: Students use VR headsets to deal with dynamic risks such as reactor leakage and diffusion, and KG-CSE simultaneously pushes personalized learning resources. Interdisciplinary collaboration: Establish interdisciplinary learning groups to simulate the collaborative work mode of multiple departments in the enterprise.

4.2. Flipped Classroom Practice

Utilising the blended learning framework, we reformulate the three-stage instructional cycle of "pre-class, in-class, and post-class".

Students internalise knowledge prior to class by completing foundational learning tasks through micro-teaching videos and KG-CSE. Advanced training in class: emphasising intricate scenarios to provide comprehensive seminar activities. Students employ dynamic fault tree analysis to delineate the origins of explosions in chemical plants. Subsequently, they replicate various emergency responses on a digital twin platform to evaluate outcomes. This equips them to assess evolving dangers instantaneously. Post-course competency enhancement: assign open-ended engineering challenges. Motivate students to create prototypes utilising open-source simulation tools and to disseminate and critique their solutions within online communities.

4.3. School-Enterprise Collaborative Teaching

Establishing a "dual-teacher" educational community to achieve a seamless integration of industrial requirements and educational objectives:

Feedback on pedagogical approaches from corporate case studies: implementing practical modules in DuPont Process Safety Management activities, such as safety document evaluations and equipment inspections. Industry engineers assist students in assessing compliance with safety regulations in conventional procedures.

Creation of high-fidelity virtual training situations for chemical firms, exemplified by the safety inspection of ethylene cracking unit. Incorporate real-time production data such as DCS alarm records, replicate the emergency decision-making process during abnormal operational situations, and improve the realism and immediacy of the instructional scenarios.

The mechanism for teacher competence training involves a collaborative workshop between university educators and industry instructors, equipping teachers with proficiency in advanced industry tools, including Aspen HYSYS dynamic simulation software and Exida SIL validation tool, to ensure that the instructional content remains aligned with technological advancements.

5. Optimization of the Evaluation System

5.1. Process Evaluation: a Dynamic Data-Driven Feedback Mechanism

Utilising Kirkpatrick's four-level assessment model, we develop an intelligent evaluation system including the entire continuum of "reaction-learning-behavior-results".

Behavioural analysis in education: employing educational data mining technology to gather students' operational logs from virtual training platforms, including HAZOP analysis software and leakage simulation systems, focussing on metrics such as decision-making response time and risk identification accuracy. By recognising standard learning patterns, including conservative decision-makers and aggressive interventionists, and producing tailored competency diagnostic reports.

Real-time feedback intervention: create an intelligent diagnostic system utilising a Bayesian network to forecast probable competency deficiencies, such as inadequate protective layer analysis and SIL grading inaccuracies, based on students' operational trajectories, and deliver tailored remedial resources to students.

5.2. Competency-Based Evaluation: a Multidimensional Quantitative Assessment Model

The Analytic Hierarchy Process (AHP) empowerment model involves the deconstruction of capability indicators based on the CCPS chemical safety capability framework. This evaluation system comprises four primary indicators and twelve secondary indicators. The primary indicators include risk identification, engineering decision-making, emergency response, and ethical compliance, while the secondary indicators encompass aspects such as HAZOP node division accuracy and emergency plan completeness index. Consult industry experts to assess the significance of each signal and verify the evaluation system aligns accurately with industry requirements.

Application of Fuzzy Comprehensive Evaluation (FCE): An evaluation matrix is established, incorporating a five-tier assessment framework that includes excellent, good, average, satisfactory, and unsatisfactory classifications. Coordinate educators, business mentors, and team members to do multi-source evaluations of students' project outcomes, including safety assessment reports and emergency drill films, utilising the 360-degree review methodology. The membership function is computed, employing a triangular fuzzy number to analyse subjective evaluation data, followed by a synthetic operation in conjunction with the AHP weight matrix to derive the quantitative ability score, thereby effectively mitigating bias from a singular evaluation subject (Garay-Rondero, 2024).

5.3. Industry Benchmarking: Certification-Oriented Proficiency Testing

International standard embedding: the essential competency requirements for chemical process safety certification are converted into course assessment modules. Students may obtain pre-certification credits by fulfilling specified tasks. Enterprise real-world simulation: utilising the Aspen HYSYS dynamic simulation platform, students must conduct a safety review for actual operational conditions in enterprises, including the process modification plan of a Sinopec refinery, with assessment outcomes directly correlated to the competency model for enterprise engineering positions.

5.4. Formative Evaluation and Archival Construction

Blockchain technology is used to build a tamper-proof e-portfolio to continuously record students' course participation data, which supports the long-term tracking and visualization of students' ability growth. At the same time, students are required to submit cognitive logs on a regular basis, and natural language processing technology is used to analyze the improvement trajectory of their risk decision-making logic, such as the increase in the frequency of the keyword "probabilistic risk assessment", which promotes the development of students' self-efficacy and critical thinking.

6. Optimization of the Evaluation System

6.1. Analysis of Key Challenges

6.1.1. Technology Integration Barriers

The development of a virtual simulation platform is complex; high-precision chemical accident simulations necessitate the integration of computational fluid dynamics (CFD), equipment failure probability models, and other multidisciplinary technologies, alongside challenges related to synergistic optimisation of cross-engine data compatibility and real-time rendering computational demands. Cost of dynamic maintenance for knowledge graphs: KG-CSE must consistently incorporate updates on international standards, accident instances, and developing risk data, while confronting the technological challenges of purifying diverse data from several sources and dynamically reconstructing semantic links.

6.1.2. Educational Resource Constraints

Constraints on hardware investment: the elevated procurement and maintenance expenses associated with AR/VR practical teaching equipment and industrial-grade simulation software hinder the widespread adoption among small and medium-sized colleges. The instructors' team often lacks proficiency in digital teaching design and familiarity with industrial software operation, hindering effective management of technology-enhanced teaching methods.

6.1.3. Absence of School-Enterprise Synergy Mechanism

Conflicts regarding intellectual property rights: the real-time production data and process parameters supplied by companies contain trade secrets, while the university must navigate the dual challenges of data desensitisation compliance and intellectual property rights sharing agreements in the development of virtual training resources.

Disparate incentive for collaboration: a conflict exists between the immediate profit requirements of businesses and the enduring educational objectives of universities, resulting in the unsustainability of joint teaching initiatives.

6.2. Response Strategy Design

Technology integration and optimisation: establish an open-source technological ecosystem, encourage colleges and universities to collaboratively develop an open-source chemical safety teaching toolkit, such as Python-based HAZOP auxiliary plug-ins, and facilitate algorithm sharing and iterative optimisation through the GitHub collaborative community, thereby lowering the barriers to the development of the simulation platform.

Collaborative allocation of educational resources: establish a cooperative framework involving government, industry, academia, and research institutions, leveraging the Ministry of Education's initiatives for industry-university collaboration and cooperative education projects. This will guide chemical enterprises, technology providers, and universities to jointly establish a "chemical safety education consortium", facilitating the systematic contribution of resources such as equipment donations, teacher training, and curriculum development. Execute the teacher capacity enhancement plan, develop the "dual-track" training framework, facilitate teacher participation in industrial software certification training within the technical track, and conduct digital curriculum design workshops in the pedagogical track to augment the proficiency of technology-teaching integration (Matt Osborne, 2024).

University-enterprise interest balancing mechanism: establish a data security collaboration framework in accordance with the Data Security Law standards, develop a tiered data sharing agreement, allowing unclassified data to be utilised directly for educational purposes, while sensitive data is processed through differential privacy to create a synthetic dataset for instructional use. Establish a long-term collaborative and incentive framework wherein universities offer tailored security training services to employers, while enterprises contribute to course development through a "talent reserve", so creating a reciprocal value-added loop of "talent supply - technology feedback".

7. Conclusions

This study addresses the reform requirements of the Chemical Safety Engineering course for safety engineering majors, establishing a comprehensive four-in-one reform framework comprising "goal reconstruction - content iteration - technology empowerment - evaluation innovation", which effectively meets the competency structure demands of safety professionals in response to the intelligent transformation of the chemical industry. This reform program was piloted in the Chemical Safety Engineering course in the spring semester of 2025 for the safety engineering major of Nantong Polytechnic Institute, and two teaching classes with a total of 79 students were selected to carry out the reform. The pilot content covers the reconstructed course modules and AHP-FCE assessment system, see Table 1 for details, and the implementation cycle is 8 weeks.

Through the analysis of the learning behavior log of the virtual simulation platform, the students in the pilot class showed significant ability improvement: the risk response speed increased by 40%: in the VR drill of the leakage accident, the average decision-making time of the students was also greatly improved compared with the previous year; 35% increase in engineering decision optimization rate: In the "reactor overpressure" multi-objective optimization scenario, the number of proposals submitted to successfully reconcile safety-cost-efficiency constraints increased from 42% in the baseline period to 77%. Meanwhile, after the course, questionnaire feedback was collected from four dimensions: timeliness of dynamic knowledge base, immersion in VR scenarios, realism of enterprise collaborative tasks, and accuracy of AHP-FCE evaluation, in which the positive evaluation rate was more than 80%. The specific competencies that students learn in this course need to be verified in the subsequent graduation internship enterprises. The data on the effectiveness of this teaching reform will be updated subsequently, and the effective reform results of this course will be applied to other courses and majors.

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