Enhancing Pipe and Diagram Processes with a Virtual Reality Simulation

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A VR-Based Supplemental Simulation to Enhance Learning Outcomes for Piping and Instrumentation Diagrams and Related Chemical Process Safety Concepts

Abstract

This paper describes the development and planned evaluation of a supplemental virtual reality (VR) simulation for a chemical engineering course on process safety at a large, Midwestern, R1 research institution. The course centers on interpreting and annotating piping and instrumentation diagrams (P&IDs), prioritizing hazards, and documenting risk-mitigation strategies. Traditionally, these skills are taught using paper-based methods that, while effective for foundational learning, can limit students' ability to visualize complex system interdependencies and anticipate the long-term consequences of their decisions.

The evaluation will use a mixed-methods approach that combines quantitative and qualitative data. Quantitative assessment will use structured rubrics aligned with ABET outcomes to measure technical proficiency and process-safety skills. Qualitative assessment will include guided reflections and instructor observations focused on the development of entrepreneurial mindset (EM) habits as defined by the KEEN framework and the Habits of EM document. These habits—implications thinking, risk assessment, accountability, and systems thinking—will be made explicit to students through targeted prompts and feedback within both the VR and paper-based components.

Keywords: virtual reality (VR); process safety; piping and instrumentation diagrams (P&IDs); simulation; entrepreneurial mindset (EM).

Introduction and Motivation

Settings and participants

Participants are undergraduate chemical engineering students enrolled in a required process safety course at a large, Midwestern, R1 public research institution. The intervention is designed to enhance learning outcomes related to comprehension and use of piping and instrumentation diagrams (P&IDs) while reinforcing relevant process hazards analysis (PHA) practices consistent with industrial practice. Observers for the simulation include graduate teaching assistants (GTAs), faculty, and industry partners. Implemented during scheduled class hours, the study uses a pretest–posttest control-group design to evaluate the impact of VR on student learning. Quantitative data collection enables calculation of effect sizes to support robust statistical analysis. Process safety content in chemical engineering is required under ABET accreditation standards; at the study institution, these requirements are fulfilled through this required undergraduate course. Based on industry feedback, the instructional team requires students to demonstrate competencies in interpreting P&IDs and using that interpretation to conduct PHA-based risk assessments using a manual, paper-based approach. Student learning is assessed through an end-of-semester case-study presentation in which students analyze a publicly available case, identify hazards, document risk-mitigation strategies, and present findings to industry participants.

This approach is well regarded by industry participants during the end-of-semester safety poster session. While the current foundational technique is effective for building core, job-ready skills, it can limit the authentic experience of being on-site in a laboratory—specifically, students' ability to visualize complex system interdependencies and anticipate the long-term consequences of their decisions. As part of a continuous improvement framework and the instructional team's reflective practice, a key limitation identified in PHA education that integrates P&ID comprehension is the challenge of visualizing these interdependencies. Recognizing this limitation, a supplemental virtual reality (VR) framework was developed by a multidisciplinary team of instructional design and chemical engineering contributors under the guidance of a faculty advisor.

Learning Objectives

The course learning objectives emphasize not only technical proficiency in interpreting risk matrices and annotating P&IDs but also the cultivation of EM habits such as systems thinking, risk prioritization, and ethical accountability. By immersing students in a simulated process environment, this research evaluates VR as a supplement to paper-based assessment, focusing on student and instructor perspectives on learning outcomes and mindset development.

Simulation Design

Because the VR application is currently under development, this paper outlines the instructional context, planned features, and assessment strategy, with the understanding that details may evolve as the project progresses. The goal is to foster deeper learning and mindset growth while maintaining the rigor and reliability of traditional paper-based assessment. Accessibility is a core design consideration. In addition to the VR headset experience, a non-VR desktop application will be available, offering video walkthroughs and parallel prompts to ensure all students can participate regardless of technological access or physical constraints. Student survey responses and instructor observations will be used to identify accessibility-related affordances and limitations.

Although VR-based systems offer many advantages, limitations related to development cost and socioeconomic access are well documented. VR implementation can also present health and usability concerns, including motion sickness and dizziness. Because the course is already well regarded by industry partners, additional funding (e.g., to hire a professional game developer) is out of scope.

To manage costs, we adopted a lean model that uses student developers in conjunction with open-source software (Godot) to create free, accessible simulations. The choice of Godot reflected the student developers' preference for source-code customization. To mitigate dizziness and improve access, the project also provides a desktop alternative, allowing students to experience the simulation on a standard monitor with a keyboard and mouse. Three-dimensional models replicate core processes chemical engineers use to assess risk and diagnose system failures. Students can virtually assemble and disassemble equipment within the simulated environment, directly manipulating components such as valves, pumps, and sensors. Each action—connecting, removing, or adjusting a part—triggers changes in system variables and initiates realistic reactions within the laboratory setup. These dynamic interactions allow students to observe how equipment configuration affects process safety, risk levels, and operational outcomes. By experimenting with different scenarios, learners gain insight into the consequences of their decisions, reinforcing both technical understanding and the mindset habits emphasized in the course.

- Instructional prompts within VR target EM habits (e.g., asking students to predict downstream consequences of process changes or failures).
- Student reflections are captured in VR and exported for instructor review.
- The VR content is strictly supplemental; all graded work remains anchored in the paper-based process.

Research Questions and Hypotheses

We hypothesize that students will demonstrate higher post-assessment rubric scores in P&ID interpretation and risk prioritization after VR-supplemented practice than after baseline paper-only assessment.

- RQ1: How does VR, compared with paper-based representations, influence engineering students' understanding of process flow and instrumentation and their ability to explain it?
- RQ2: How does VR supplementation, compared with paper-only instruction, influence the depth of systems thinking, risk awareness, and accountability evident in student reflections?

Methods

The study builds on the course's existing P&ID safety matrix and learning objectives. To measure students' engagement and learning during VR use, we will administer a mixed-methods survey to capture student feedback on experiences with both modalities.

Study Design

Within-subjects crossover: All students complete a paper-based P&ID and risk assessment (baseline), then a VR-supplemented practice activity, followed by a paper-based post-task on a parallel scenario. The paper process is the graded anchor; VR adds practice and reflective prompts.

Instruments and Data Sources

- **Artifacts:** Paper-based P&ID/risk assessments (baseline and post), VR activity logs, embedded reflection responses.
- **Reflections:** Guided reflections after each modality, with a capstone comparative reflection.
- **Surveys:** EM-aligned self-assessment, VR usability/acceptance.
- **Instructor Assessment:** Analytic rubric scored by instructors/TAs, observation checklists during VR sessions.

Assessment

The assessment strategy for the virtual reality (VR) framework uses a mixed-methods approach, integrating quantitative and qualitative measures to evaluate both technical learning outcomes and mindset development. The design is informed by established models in engineering education research, including Buń et al., and is adapted to the context of process safety and risk-management instruction.

Implemented during scheduled class hours, the study uses a pretest–posttest design to evaluate the impact of VR on student learning. Structured rubrics aligned with ABET outcomes will be used to measure technical proficiency and process-safety skills, enabling calculation of effect sizes for statistical analysis. Guided reflections and instructor observations will be used to examine entrepreneurial mindset (EM) habits as defined by the KEEN framework. Survey data will be used to contextualize and triangulate rubric-based performance measures rather than serve as direct evidence of mastery. While ABET-aligned rubrics capture observable performance outcomes, EM habits are assessed through reflective and behavioral indicators triangulated across modalities.

Quantitative Assessment

Student performance is evaluated using analytic rubrics aligned with ABET outcomes and KEEN entrepreneurial mindset (EM) habits. Each rubric item is mapped to specific course learning objectives, such as proficiency in interpreting P&IDs, risk prioritization, and ethical accountability. Rubrics use a three- to four-level scale (e.g., Beginning to Exemplary), with descriptors anchored in EM-habit language to support clarity and scoring consistency.

In the within-subjects crossover design, all students complete a baseline paper-based P&ID and risk assessment, followed by VR-supplemented practice, and then a post-task paper assessment on a parallel scenario. This structure supports direct comparison of learning gains attributable to the VR intervention while controlling for individual differences in prior knowledge and experience.

To assess perceived usefulness and ease of use of the VR system, we plan to administer a validated technology-acceptance questionnaire. The instrument consists of 13 items rated on a five-point Likert scale and has demonstrated reliability (Cronbach's alpha > 0.8). This measure provides insight into student attitudes toward the VR modality and its integration into the curriculum.

Qualitative Assessment

Students complete structured reflection prompts after each modality (paper and VR), as well as a capstone comparative reflection. Prompts are designed to elicit insights into system understanding, modality strengths and limitations, engagement, problem-solving, and real-world application. Thematic analysis of these reflections is conducted using a codebook derived from EM habits, enabling identification of patterns in mindset development and learning experiences.

During VR sessions, instructors and teaching assistants use observation checklists to document student behaviors, decision-making processes, and engagement levels. These observations are triangulated with artifact analysis and reflection data to provide a comprehensive view of student learning.

Survey Design

Recognizing the diversity of student needs and technological resources, the assessment framework includes non-VR alternatives (e.g., walkthroughs and demos) to ensure equitable participation. Ethical considerations, including IRB exemption, grade neutrality, and privacy protections are integrated into the assessment process. The technology-acceptance questionnaire used in prior work, such as the instrument developed by Chu, Hwang, Tsai, and Tseng, consists of 13 items rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

The questionnaire includes six items for perceived usefulness (e.g., "The learning system helped me obtain useful information when needed") and seven for perceived ease of use (e.g., "It is not difficult for me to learn to operate the learning system”). Cronbach’s alpha values for the two dimensions were 0.84 and 0.86, respectively, indicating acceptable reliability.

The assessment will be conducted during the fall semester and will conclude in the spring semester. Table 1, the reflection prompts, and the procedure table provide details and a timeline.

Table 1. Student survey questions

Statement	ABET Outcome	Benchmark Description	Scale
I understood the process flow and instrumentation better using the paper-based diagram.	Outcome 1	Ability to identify, formulate, and solve complex engineering problems.	1–5
I understood the process flow and instrumentation better using the VR-based diagram.	Outcome 1	Ability to identify, formulate, and solve complex engineering problems.	1–5
The paper-based format helped me visualize system relationships effectively.	Outcome 2	Ability to apply engineering design to produce solutions that meet specified needs.	1–5
The VR format helped me visualize system relationships effectively.	Outcome 2	Ability to apply engineering design to produce solutions that meet specified needs.	1–5

I could clearly explain the process flow and instrumentation to others using the paper-based diagram.	Outcome 3	Ability to communicate effectively with a range of audiences.	1–5
I could clearly explain the process flow and instrumentation to others using the VR-based diagram.	Outcome 3	Ability to communicate effectively with a range of audiences.	1–5
I felt more engaged and focused when using the paper-based format.	Outcome 5	Ability to function effectively in a team and communicate effectively.	1–5
I felt more engaged and focused when using the VR format.	Outcome 5	Ability to function effectively in a team and communicate effectively.	1–5
I can see how the paper-based format connects to real-world engineering tasks.	Outcome 4	Ability to recognize ethical and professional responsibilities in engineering situations.	1–5
I can see how the VR format connects to real-world engineering tasks.	Outcome 4	Ability to recognize ethical and professional responsibilities in engineering situations.	1–5

I prefer paper-based formats for learning technical diagrams.	Outcome 7	Ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	1–5
I prefer the VR format for learning technical diagrams.	Outcome 7	Ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	1–5

Open ended reflection prompts

Open-ended reflection prompts complement the mixed-methods approach by giving students space to share ideas and feedback that quantitative data may not capture. Students will enter these responses in the survey using a text field.

Understanding the System

How did each modality help you understand the process and instrumentation diagram? Which format supports your learning more effectively?

Modality Strengths and Limitations

What are the strengths and limitations of each format? Consider clarity, accessibility, and how each supports your learning.

Engagement and Learning Experience

How did each format affect your engagement and motivation? Did one modality help you stay more focused or curious?

Problem-Solving and Visualization

How did each format support your ability to troubleshoot or visualize the system?

Real-World Application

Which format better prepares you for professional engineering practice or lab work?

Your Preference and Justification

Which modality do you prefer overall, and why?

Procedure, Data, and Implementation Notes

The following outlines the processes and procedures used during a recent offering of a required undergraduate chemical engineering process safety course at the study institution. The course is offered regularly as a core, ABET-aligned requirement. All undergraduate chemical engineering students at the study institution complete this course as part of the core curriculum over a multiyear period.

Procedure

1. **Paper baseline:** Students complete a standard P&ID-based hazard analysis and risk assessment (first two weeks of the fall semester).

2. **VR session (supplemental):** Students complete a guided VR scenario with embedded prompts targeting EM habits (week 3 of the spring semester).

3. **Paper post-task:** Students complete a second paper-based assessment on a parallel scenario (last two weeks of the spring semester).

4. **Reflections:** Immediate and comparative reflections after each modality.
5. **Instructor Review:** Artifacts are scored with the EM rubric; observations are logged during VR.

Data and Evaluation Plan

- **Primary Outcome:** EM rubric gains from baseline (paper) to post (paper after VR).
- **Secondary Outcomes:** Reflection richness, implication steps, risk prioritization accuracy, accountability markers.
- **Process Measures:** VR usability/acceptance, time-on-task, error counts in P&ID interpretation.

Implementation Notes

<u>Technology:</u> Headsets are used to immerse students in the VR environment, enhancing engagement and realism. A safe-use orientation ensures all participants are familiar with health and safety protocols before beginning. The seated-mode option accommodates users with mobility needs, promoting accessibility and comfort. A mirrored display enables peers to observe the VR session in real time, supporting peer learning and feedback. Institutional support services will support headset access, and the application is designed to run locally on the hardware, minimizing dependence on Wi-Fi, and safeguarding secure data needs. Importantly, no user data will be collected during the experience, ensuring privacy.

<u>Accessibility:</u> Recognizing that not all users have access to VR equipment or the ability to physically wear the headset, the platform provides a non-VR alternative featuring video

walkthroughs and matching prompts, which are easily accessible via laptop or desktop computers. The approaches ensure that individuals with varying needs or technological resources can still engage with the content, making the experience more inclusive and adaptable for educational or personal use.

Ethics: IRB/educational exemption, consent, grade neutrality, privacy for analytics.

Discussion and Preliminary Findings

The preliminary findings derive from an early exploratory survey and do not represent outcomes of the full crossover study. The results suggest improvements in learners' P&ID-related outcomes, while also indicating areas for improvement.

Preliminary Findings

In a fall-semester class, students were surveyed about their experience using the VR application and their perceptions of the transition from traditional paper-based instruction to a VR-supplemented framework. Findings are organized by efficiency, instructional design preferences, and the qualitative impact on visualization and engagement.

Gains in System Comprehension Efficiency Historically

Students reported that approximately 60 percent of their time was dedicated to "learning the system" using traditional paper-based P&IDs. When asked to predict the impact of VR, 24 of 35 respondents estimated that future classes would need only 21 to 50 percent of their time to master the system through simulation. This projected reduction suggests that an immersive environment may accelerate technical proficiency, potentially freeing classroom time for more complex risk-assessment tasks.

Instructional Scaffolding and "Sandbox" Preferences

The data indicates a strong preference for structured instructional design over purely open-ended exploration. Fifteen students preferred an even balance between guided instruction and “sandbox” learning, while 11 students preferred a more guided approach. Only three students expressed a preference for a primarily “sandbox” environment. This preference underscores the importance of clear prompts and tutorials to help students navigate the complexity of chemical process simulations.

Usability and Visual Learning Aids Students

Students’ verbal feedback found the interactive cues in the VR environment useful for learning P&ID. Behavioral prompts like hover text and ghost shading on movable parts were rated highly for their helpfulness. The survey included open-response items for qualitative feedback; one student noted that VR helped them “visualize the flow” and “connect the P&ID symbols to the real units they represent.” Another remarked that the simulation helped the “paper form come to life,” enabling a deeper understanding of internal mechanics that are often invisible on a flat diagram.

Engagement and Desire for Realistic Consequences

To enhance engagement, students expressed interest in real-time feedback mechanisms, such as displayed scores (more than 40 percent interest) and a larger inventory of components. Several students also requested more realistic consequences for errors, such as the “burner exploding” if a mistake is made. This aligns with the framework’s goal of teaching accountability by making the consequences of engineering decisions visible and concrete.

Challenges and Areas for Improvement

Student feedback also noted a learning curve related to software navigation. Concerns included difficulty understanding controls without a comprehensive tutorial and a need for a complete list of keyboard commands. These insights suggest that while VR can improve visualization, the initial onboarding process must be robust so that technology does not become a barrier to learning.

Limitations

Because of development constraints and limited access to VR hardware, only one headset was available. To accommodate the class, students also used a desktop version of the application. Some stakeholders, including faculty and industry observers, were unfamiliar with the keyboard controls and required brief tutorials to operate the simulation.

Future Work

Future work includes exploring augmented reality (AR) technologies, such as glasses that overlay text and charts. Additional revisions may include fault trees and scenario-based levels within the application. These additions would support the design of both real-world machines and digital twins. With sufficient access to machinery and computer science development support, scalable digital twins could be replicated to test "chaos" scenarios without introducing real-world risk. The team also plans to develop a brief pre-simulation video tutorial that explains the controls and the goals of the experience.

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