Collaborative Research: Designing an Immersive Virtual Environment for Chemical Engineering Process Safety Training

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Jeff joined the field of engineering education after receiving his Bachelor of Science in Mechanical Engineering from Rowan University in May 2019. He conducted research as part of his senior design course on the analysis of Process Safety Decision Making data gathered from a digital immersive environment. He will continue his research on engineering student behavior towards a doctoral dissertation through Rowan's ExEEd Engineering Department under the U.S. Department of Education Graduate Assistance in Areas of National Need (GAANN) Fellowship Program Grant Number P200A180055.

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Dr. Matthew Cooper is a Teaching Associate Professor in the Department of Chemical and Biomolecular Engineering at NC State University where he teaches Senior Design, Material and Energy Balances, Unit Operations, Transport Phenomena and Mathematical/Computational Methods. He is the recipient of teaching and pedagogical research awards including the NCSU Outstanding Teacher Award, ASEE ChE Division Raymond W. Fahien Award and the 2013 and 2017 ASEE ChE Division Joseph J. Martin Awards for Best Conference Paper. Dr. Cooper's research interests include effective teaching, process safety decision-making skills and best practices for online education.

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Introduction & Background

Industrial process safety incidents are unfortunately a fixture in the daily news cycle [1]. In response to these incidents, universities are now required by ABET to include process safety instruction as part of their chemical engineering (ChE) program's curriculum, specifying that programs must "include the engineering application of these basic sciences to the design, analysis, and control of chemical, physical, and/or biological processes, *including the hazards associated with these processes*" [2]. Typical approaches to address this ABET requirement in classrooms include education related to "prevention through design (PtD)" measures such as inherently safer design and proper use of personal protective equipment (PPE) [3,4].

Unfortunately, PtD approaches do not address the topic of human decision making, which has been found to be the root cause of a number of process safety incidents [5-7]. For instance, an incident involving the accidental launch of a US nuclear missile was caused by a worker simply deciding against spending time to retrieve an appropriate torque wrench for their task. When the worker's inappropriate ratchet was dropped during a repair, it damaged a fuel tank and caused a leak. Upon the leaking fuel's ignition, the warhead was propelled from the silo, landing over 100 feet away. Fortunately, the radioactive warhead did not detonate, but one individual was killed and twenty-one individuals were injured in the incident [8,9].

Teaching and assessment of decision-making strategies has challenges in a typical classroom environment. In classroom or test scenarios, students tend to decide an action that sounds the "safest" is the correct choice. In other words, since students know they are taking a test on process safety decision making, they tend to state they will make the safest-sounding decision, leading to inauthentic student responses. Similarly, in-class discussions, tests, etc. do not capture factors such as time or money constraints, or coworkers' influence that may alter decisions in the real world and reveal a different level of moral development and understanding.

In this work the research team is seeking to develop ways to safely allow students to make more authentic safety decisions. To this end, the team has developed and implemented two instruments: (1) an analog or "paper" instrument to assess levels of moral development with respect to process safety, and (2) a virtual process safety decision making environment [10-13].

Project Objectives

To assess the effectiveness of these two different interventions on process safety education, the team asked the following research questions: 1) Is there a change in students' process safety decision making skills based on their use of the virtual environment? 2) Does the use of the virtual environment increase students' motivation to learn about process safety? 3) Are there demographic differences in the students' responses to Questions 1 and 2?

To begin to answer Research Question 1 and to quantitate differences in student process safety reasoning, the research team developed and validated the Engineering Process Safety Reasoning Instrument (EPSRI), which has been described elsewhere [10-13]. Students at the researchers'

home institutions were given the EPSRI at the start and the end of a senior design or professional practice course. The goal of this implementation was quantify students' process safety decision making ability with normal exposure to typical chemical engineering coursework (i.e. in the absence of the developed virtual environment). To answer Research Question 2, the research team used the well-established MUSIC (eMpowerment, Usefulness, Success, Interest, and Caring) model for academic motivation and engagement [14-16].

To continue answering Research Questions 1 and 2, the team developed and deployed a virtual environment entitled "Contents Under Pressure", described in the following section. Students were given access to the virtual environment, with the EPSRI and MUSIC model instruments surveying students both at the beginning and end of a senior design or safety course. The analysis of the data obtained from these interactions will ultimately be compared with the students who took the EPSRI previously but only received traditional process safety instruction.

Methods

This past year, the research team worked with Filament Games to create the virtual environment. The development of the virtual environment involved a collaborative four month design process with input from a variety of stakeholders from both the research team and Filament Games with expertise in areas such as computer programming, visual and sound effects, process safety content knowledge, and user interface design.

The storyline for "Contents Under Pressure" follows a fifteen-day narrative where participants play as a chemical plant manager for an average of five to seven minutes per day. The limitation on the amount of interaction on a daily basis was done strategically to ensure that the virtual environment would become integrated within the participant's daily schedule and as such be more likely to accurately capture the approach a participant might take in making process safety decisions. The narrative arc follows the plant manager as they ensure strong productivity and safety of the chemical plant while faced with an incoming hurricane. The manager interacts with a number of different characters including their own supervisor, a safety supervisor, three subordinate operators, a newscaster, and their adopted daughter. Each of these characters brings dimension to the virtual environment as they challenge the participant with diverse decisions. An example of a screenshot within the digital immersive environment can be seen in Figure 1.

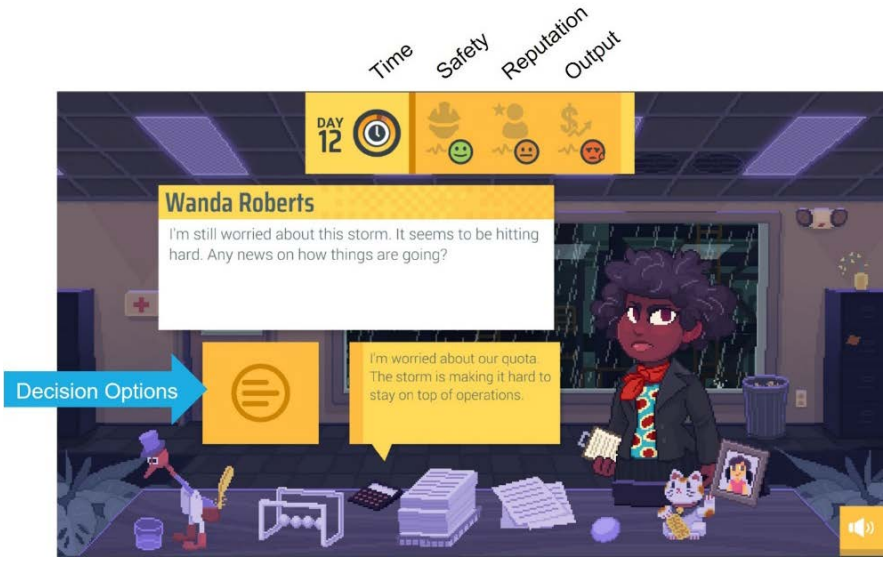

Figure 1. Example screenshot from "Contents Under Pressure"

In "Contents Under Pressure", the participant is shown decision prompts that have two potential responses. Each potential response will influence four metrics that record participant behavior within the environment. The first metric is time, represented by a clock that changes as decisions are made. The other three metrics are safety, personal reputation, and output. Performance on these metrics is shown by an icon that indicates relative performance (i.e, a smile indicates good performance, a frown indicates negative performance, etc.). Within the virtual environment, participants are also given reflection prompts that seek to better understand the conditions that might have influenced their decisions. Reflection prompts were designed in alignment with Kohlberg's moral development theory and include pre-conventional, conventional, and post-conventional levels of reasoning [17]. An example reflection prompt is shown in Figure 2.

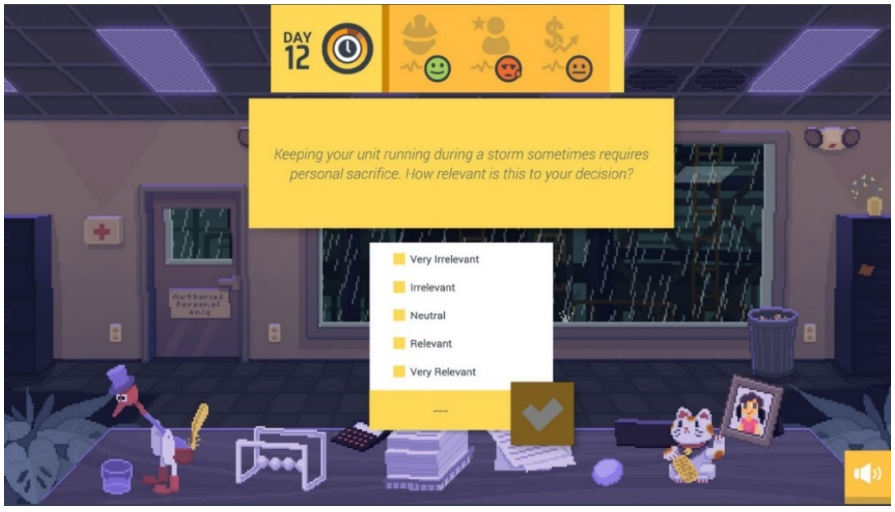

Figure 2. Reflection prompt screenshot from "Contents Under Pressure"

Pilot testing of "Contents Under Pressure" was performed during the Spring 2019 semester to determine how the virtual environment was perceived by students and what modifications may be needed for future use. Formal feedback was obtained through students' completion of Jones'

MUSIC model of academic motivation survey as described in the literature [14-16], and informal feedback was obtained in the form of student comments. MUSIC model measures students' academic motivation based on student responses to prompts relevant to five motivational constructs: eMpowerment, Usefulness, Success, Interest, and Caring. Results from the MUSIC model of academic motivation from the Spring 2019 pilot test are shown in Table 1.

Table 1. Student Ratings of Academic Motivation in Response to "Contents Under Pressure"

Motivational Model Element	Average	Std. Dev.
Empowerment	4.72	0.96
Usefulness	4.41	1.04
Success	4.85	0.80
Interest	4.90	0.90
Caring	4.85	0.76

Table 1 shows that students gave high scores in all the MUSIC model constructs with ratings between a 4 (somewhat agree) to a 5 (agree). These results suggest that students felt the digital immersive environment was a useful tool that provided them the possibility of a successful outcome while being of interest to them.

A variety of informal feedback was also obtained from students. Many of the students felt that the digital immersive environment accurately reflected what might occur in the working world but were frustrated that making decisions to prioritize safety could result in economic impacts to the plant. They also commented that they felt connected to the characters and as such would modify their approaches to decisions based on the emotional attachments they were forming. Students also felt the outcomes of their decisions as indicated by changes in the meters wasn't quite what they expected. Some students were able to consistently reach high safety scores even when they didn't consistently select the "safest" option for a decision. All of the informal feedback obtained was taken back to Filament Games and used to improve upon the participant experience for the subsequent implementation of "Contents Under Pressure".

Current Status and Future Work

Students at three institutions completed "Contents Under Pressure" during the Fall 2019 academic term as part of various senior-level chemical engineering courses. Students completed the EPSRI both before and after interacting with the virtual environment. The version of the EPSRI used matched the version implemented in Fal1 2018, where it was administered before and after traditional safety and ethics instruction without the use of the virtual environment. This approach allowed for the tracking of students' moral reasoning with traditional instruction and with instruction augmented with the virtual environment. Furthermore, student responses to the reflection prompts within "Contents Under Pressure" are also currently being analyzed by mapping them to Kohlberg's levels of moral development. When complete, this analysis and

comparison between the two platforms will allow for the research questions, as described previously in the Project Objectives, to be answered.

At this time, we are in the last phase of reliability assessment for the EPSRI through data collection to allow for a confirmatory factor analysis to be completed. Further development of "Contents Under Pressure" will include balancing individual situation prompts to assure that points are added and deducted from appropriate categories at appropriate magnitudes to make the game challenging but still completable. With additional resources, "Contents Under Pressure" may receive additional narrative complexity, with certain decisions shifting the narrative of the experience in new directions. This modification could allow students to experience the virtual environment multiple times for practice with a wider range of possible outcomes.

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