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Impact of Immersive Training on Senior Chemical Engineering Students' Prioritization of Process Safety Decision Criteria

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Introduction

Process safety is becoming a greater focus of chemical plant design and operation due to the number of incidents involving dangerous chemical accidents [1]. Since its creation nearly 20 years ago, the Chemical Safety Board (CSB) has investigated 130 safety incidents and provided over 800 safety recommendations to operating chemical facilities. Following a gas well blowout in 2018, the CSB gave a recommendation to the American Petroleum Institute (API) to establish recommended practice on alarm management [2]. Similarly, in 2017, the CSB gave a recommendation to Arkema Inc. to update their emergency response training following a hurricane that caused a fire at one of their manufacturing sites [3]. Many times, CSB-led investigations resulted in new regulations and standards that are enforced by the Occupational Safety and Health Administration (OSHA) or the Environmental Protection Agency (EPA) [4], [5]. These critical recommendations positively impact not only the plant workers but also the surrounding community and the environment [1] .

While these safety measures enhance industrial safety culture, it is important that process safety also be integrated into university-level engineering curricula to promote safety culture while future engineers are still developing. Integrating process safety into the curriculum prepares students by familiarizing them with the difficult decisions they will be required to make in professional practice. ABET, the engineering program accreditation body, acknowledges the value of early, appropriate training within their program guidelines “Criteria for Chemical Engineering Curriculum” which states that recognition and assessment of the hazards associated with chemical processes must be included in the curriculum for program accreditation [6]. Based on this requirement, many institutions have taken the approach to integrate process safety into their curriculum using video case studies, adding entire courses to cover hazard identification, and including safety lectures in design courses[7]–[9]. A common theme missing from these methods is instruction on how to approach, recognize, and navigate decisions within a process safety context; a lack of this situational awareness was noted as a key element in industrial process safety incidents [10].

Understanding how students approach process safety decisions is important for developing teaching methods and curriculum that will better prepare them for professional practice. As part of this study, we will measure how students rank criteria associated with process safety decisions, and how these prioritizations change after exposure to a process safety decision making intervention. Through this work, we hope to determine how process safety curriculum may be improved to help better prepare students for process safety decisions within industry.

Background

Safety plays a critical role in the chemical process industry because of its potential negative impact on the health of communities and the environment if a failure occurs; Crowl and Louvar acknowledge that “ the potential always exists for an accident of catastrophic proportions” (p. 2) [11]. Engineers have implemented multiple preventative strategies such as system modeling and analysis, redundant safety valves, and alarms in an attempt to reduce the chance of failure [11], but these strategies are often found to be limited by shortcomings in human decision making [12]. There is ample reason to add process safety to undergraduate program accreditation due to past process safety incidents [13], but program changes may need to go beyond this. Human decision making has been shown to have a large impact on these incidents, so it is essential to include an emphasis on safety-conscious decision making in undergraduate chemical engineering education [7].

Process Safety Strategies

Preventative measures are the primary method to ensure safe process operations as identified by Crowl and Louvar [11]. These measures aim to minimize the probability and/or the impact of potential failures often through plant design. Some mechanisms attributing to this include duplicate pumps or holding tanks for emergency use or control systems to automatically actuate valves to regulate flow, temperature, and other variables. Implementing preventative measures is often referred to as an inherently safer design [11]. Many organizations have been established throughout the years to address the dangers of chemical plants and to help create safer chemical plant environments. Strict regulations that require a Hazard Operability (HAZOP) assessment and a Layers of Protection Analysis (LOPA) have been incorporated to ensure proper safety measures are taken [14]. If these are followed, then the result is a chemical facility where the staff have identified all existing risks and are trained to identify potential future risks during operation. While this is a step in the right direction, hazards cannot be fully eliminated. For instance, the Chevron Refinery Fire in 2012 was caused by a segment of pipe previously flagged for repair. The resulting fire injured six plant employees and an estimated 11,000 members of the community sought medical treatment, due to fume exposure. If the operators at the plant properly executed their duties, and the plant maintenance had been performed, this could have been prevented [15]. Similarly, the Pryor Trust gas well had a massive blowout in 2018 that killed 5 employees. This accident involved improper failsafe mechanisms and a series of poor process safety decisions [2]. One example of a poor decision prior to the blowout was the silencing of the entire alarm system. The decision to silence the alarm was made without first determining the source of the alarm. In both of these cases, a plant manager or other involved employees had opportunities to make decisions that would mitigate the risk of an accident, and potentially save lives. A chemical plant cannot operate on its own, so regardless of alarms, hazard analyses, safety valves, or any other preventive and reactive design measures in the process, the safety of its employees and the surrounding community ultimately rests in the hands of anyone making those real time critical decisions [16].

In order to better understand the role of decision making within chemical plants we can refer to the Swiss cheese model, which is a depiction of an organization's defenses against failure. The Swiss cheese model presents a series of barriers (or cheese) which are safety layers in a process system, as shown in Figure 1. Every hole in the slice of cheese identifies a potential weakness or failure in the system. Where these holes align through all slices, a failure will occur [17]. To understand how this model applies to process safety, we refer to the aforementioned Chevron Refinery fire. Barriers of protection may include replacing worn equipment, routinely touring the plant, and shutting down operations during an incident. Any of these barriers have the power to mitigate process safety disasters. However, at the Chevron refinery, these barriers were inhibited by human decisions. The pipe segment, which leaked, had been previously acknowledged to be at risk due to sulfidation thinning, but this barrier of protection was bypassed when the decision was made to overlook this pipe segment while inspecting for thinned pipes. Once the leak had been identified, the decision was made to keep the plant running, instead of shutting it down, aligning the holes in the final safety barrier of the Swiss cheese model. Since it is evident that human decision making is integral to the overall safety of plant operations as poor decisions can impede the effectiveness of other safety barriers, it is necessary to ensure appropriate training is provided to students before they enter the workforce.

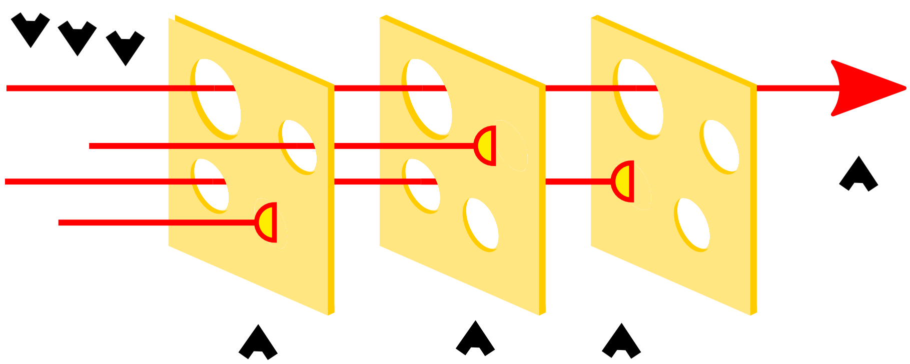

Figure 1. Example of the Swiss cheese model [18].

Process Safety Education

Since 1992, the Safety and Chemical Engineering Education (SAChE) program has helped to bring process safety to engineering schools by providing teaching materials and programs for students [19]. After the events of the T2 Laboratories explosion, ABET was advised to adapt their accreditation requirements to incorporate process safety [13], [20]. This adaptation is evident in ABET's student outcome that states that a student will demonstrate "an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts" [6]. Ever since, process safety in undergraduate curricula has been a key component in training today's engineers for their future careers [7]. However, for students who have only seen process safety situations through coursework, it may be challenging to pivot to more complex situations in a professional setting. Willey et al. acknowledged this and developed a program where students performed HAZOP analysis on the facilities of a university campus [10]. This provided students with hands-on experience in a safe environment. Although this may provide useful experience in hazard identification, students still require experience in process safety decision making to effectively prepare them for industry.

It is apparent that although it is necessary for students to learn the foundations of preventative design, all chemical engineering undergraduates should also complement this with instruction on how to approach, recognize, and navigate process safety decisions. Such efforts will help students be better prepared for professional practice.

Research Questions

The purpose of this study is to examine how senior chemical engineering students prioritize decision criteria that is relevant in process safety decision making and if this changes due to exposure to a virtual process safety decision making environment. The two research questions that this study addresses are:

1. How do senior chemical engineering students prioritize safety in comparison to criteria such as budget, personal relationships, plant productivity, and time in a process safety context?
2. How does senior chemical engineering students' prioritization of decision making criteria (budget, personal relationships, plant productivity, safety, and time) change after exposure to a virtual process safety decision making environment?

Methods

This section will contain an overview of our study design, a description of the intervention Contents Under Pressure (CUP), and discuss the data analysis performed.

Study Design

This study consisted of a semester long pre-/post- research design involving the use of CUP as an intervention. A total of 187 senior chemical engineering students, enrolled in either a senior design or process safety course from three different institutions, participated in the study. In order to understand how senior chemical engineering students prioritize criteria relevant to process safety decisions, they were asked to complete a pre-reflection where they sequentially ranked the criteria (budget, personal relationships, plant productivity, safety, and time) based on how important they thought these were within a chemical plant environment. Numerical interpretation of this ranking resulted in the most important item receiving a score of 1 and the least important item receiving a score of 5. After completion of the pre-reflection, the students were given 30 days to complete the CUP intervention. A post-reflection was then provided with the same ranking question used in the pre-reflection to determine how the game influenced the senior chemical engineering students' prioritization of process safety criteria.

Decision Making Criteria

The criteria in this study were budget, personal relationships, plant productivity, safety, and time. These decision making criteria were selected as they can be found across a variety of professions including the process industry. In the medical field, the quality and safety of patient care is influenced by financial pressures, as found in multiple studies [21], [22]. Although the contexts of the medical field and process industry differ, they both rely on high-risk decision making. Such an example promotes the role of safety and budget criteria in decision making. Construction management education highlights the importance of investing time towards planning at the beginning of a project as it impacts the site safety and project quality [23]. This example promotes the role of time, safety, and (plant) productivity criteria in decision making. These examples do not show evidence of the role of personal relationship criteria; however, affect bias, or bias derived from pleasures or fears has been acknowledged as a limitation of an engineer's judgment [24]. As such, the role of personal relationships may still exist.

Contents Under Pressure

The intervention used in this study is the immersive digital environment called *Contents Under Pressure* (CUP; shown in Figure 2). Previous detailed descriptions of CUP are provided in other sources [25], [26]. Student users are able to access this environment on their personal computers through a website link provided through their course. Within this environment, users are placed in the role of a plant manager and prompted to make various decisions throughout the course of a virtual day. Each "day" lasts roughly fifteen minutes and there are fifteen total days to the narrative.

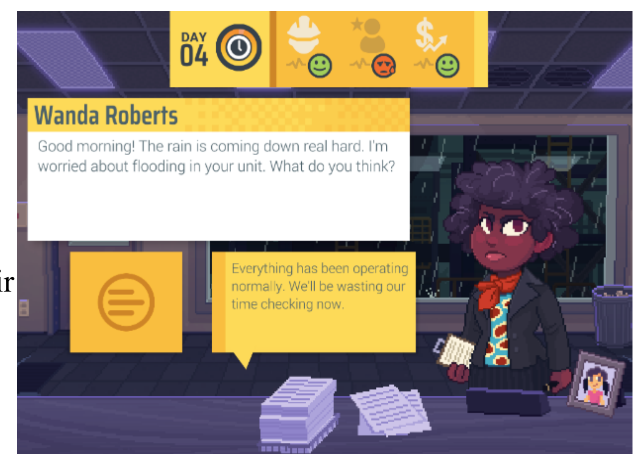

Figure 2. Screenshot of standard *Contents Under Pressure* gameplay card prompt with two possible choices.

As the plant manager, the user takes responsibility for the employees and the plant where they encounter situations including accidents, chemical leaks, and employee conflict. The climax of the narrative is a hurricane that stretches the plant and its employees to their limit.

When CUP starts, the user, acting as a mid-level manager, interacts with various characters, ranging from a safety inspector to subordinate employees to the user's own supervisor. All of the user's decisions take place in their office, as shown in Figure 2. The user responds to characters through card prompts that appear on the screen. The user can choose between two options for each dilemma they face (an example of this behavior is shown in Figure 2).

There are four meters at the top of the screen, as shown in Figures 2 and 3, that represent process safety criteria: time (shown by the clock), safety (shown by the hard hat), personal reputation (shown by the silhouette of a person with a star), and plant productivity (shown by the dollar sign). When deliberating how to respond to the dilemma presented, hovering the cursor over the response card will also highlight the meters that will be affected by that choice. No information is provided as to whether this will increase or decrease the meter reading. The status of each meter is gauged by a face that becomes sad and red when at low levels and green and happy when at high levels. The user's goal is to keep the meters as high as possible. In the event that one of these meters becomes too low, a failure is recorded as shown in Figure 3. When a failure occurs, the meter returns to the halfway mark, and the narrative resumes. These failure records alongside the final meter ratings are what ultimately determine the user's score at the end of the immersion.

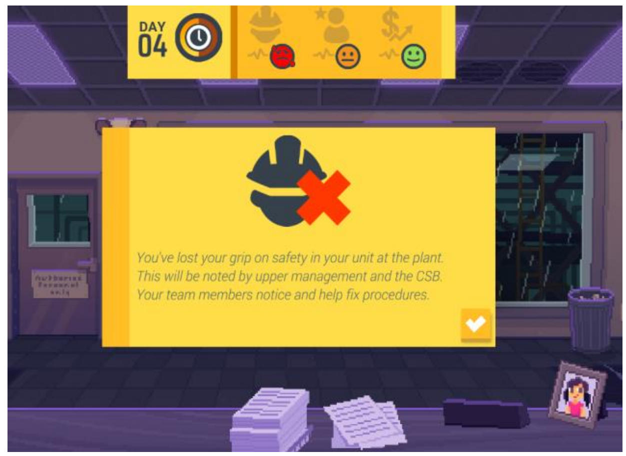

Figure 3. Screenshot of *Contents Under Pressure* failure screen from too low of a safety meter.

Some of the questions or statements presented require critical thinking and the ability to balance competing criteria. For example, in one of the prompts, it is revealed that a heavy rainstorm is predicted to hit the plant and your supervisor asks if you are going to prepare the plant for possible flooding or forego the preparations to meet your production quotas. Any deviation from the scheduled work will impair the productivity metric but preparing for the storm could improve the safety metric. This dilemma highlights how students are forced to make decisions when faced with competing criteria such as safety and plant productivity. Throughout CUP, users will make many types of decisions that force them to balance and compare competing process safety criteria such as budget, personal relationships, plant productivity, safety, and time.

Data Analysis

The first research question sought to understand how certain process safety criteria is prioritized through students' ranking. Descriptive statistics (mean and standard deviation) of criteria were calculated to preliminarily evaluate if differences in ranking existed. In determining whether there were any differences in the rankings of the criteria on the pre-reflection, we used a Friedman test and a Wilcoxon-sign-rank post hoc test due to the use of ordinal data [27]. Multiple comparisons (n=10) were made as part of the data analysis, leading to an increased probability of a false positive reading (Type 1 error), so each p-value had a Bonferroni adjustment factor of 10 applied [28]. The magnitude of difference between the rankings of criteria was evaluated using Cohen's d for effect size [29], [30].

The second research question sought to understand how the criteria prioritization changed after training with the CUP intervention. This analysis also began by calculating descriptive statistics (mean rankings and standard deviations). The same statistical comparison used on the pre-reflection data for answering the first research question was applied to the post-reflection data. In addition, response differences between the pre- and post-reflections were compared using a paired t-test with Cohen's d applied for determination of effect size [29], [30].

Results and Discussion

The purpose of this study is to gain insight in how senior chemical engineering students prioritize safety with respect to other criteria and how this prioritization changes after engagement with an immersive digital environment, CUP. This section will present results and discussion for both research questions.

Research Question 1

The first research question was *how do senior chemical engineering students prioritize safety in comparison to criteria such as budget, personal relationships, plant productivity, and time in a process safety context?* Results obtained from the student pre-reflection rankings of the process safety criteria are shown in Table 1, where a rating of 1 represented highest priority and a rating of 5 represented lowest priority. The average sequence of importance students had for these criteria were: safety, plant productivity, budget, time, and personal relationships.

Table 1. Descriptive statistics from the pre-reflection.

	Budget	Personal Relationships	Plant Productivity	Safety	Time
Mean Ranking	3.05	4.23	2.70	1.11	3.90
Standard Deviation	0.89	1.08	0.94	0.44	1.00

In order to determine if a statistical difference exists among the prioritization of criteria, a Friedman test was performed, which was found to be highly significant, p<0.001. This indicates students did perceive some criteria to be more important to their decisions than others; however, this test alone does not reveal individual prioritization differences between pairs of criteria. Thus, a post hoc Wilcoxon-signed-rank test was performed between every pair of criteria to evaluate what relationships exist. This analysis found that each comparison was highly significant (p<0.001) except when comparing the rankings of personal relationships to time, which had a slightly lower p-value (p=0.050). These results allow us to say with certainty that students perceive these criteria to have different levels of importance. We used effect size to measure the magnitude of difference in students' perceived importance of these criteria. The results of these comparisons including Cohen's d effect sizes, are given in Table 2. Only two of the ten comparisons have effect sizes that are not large or very large, which may appear alarmingly frequent. However, effect sizes from 1.2 to 3.7 simply represent that 2% to 38% of the two distributions overlap [30]. Because ranking data are ordinal instead of continuous, lacking overlapping distributions in this case may make sense.

Table 2. Comparison between pairs of criteria rankings from the pre-reflection using the Wilcoxon-signed-rank test and Cohen's d for effect size.

Criteria	P-value	Effect Size [29]
Budget - Personal Relationships	p<0.001***	1.20, large
Budget - Plant Productivity	p<0.001***	0.43, small
Budget - Safety	p<0.001***	2.62, very large
Budget - Time	p<0.001***	0.82, large
Personal Relationships - Plant Productivity	p<0.001***	1.60, very large
Personal Relationships - Safety	p<0.001***	3.77, very large
Personal Relationships - Time	p<0.050***	0.38, small
Plant Productivity - Safety	p<0.001***	2.05, very large
Plant Productivity - Time	p<0.001***	1.23, large
Safety - Time	p<0.001***	3.40, very large

Before engaging with CUP, senior chemical engineering students had ranked personal relationships to be the least important criteria to process safety decisions. In comparison to any other criteria there was a highly significant difference using the Wilcoxon-sign-rank test. As discussed, personal relationships were identified as a decision criterion because it was recognized to influence an engineer's rationalization [24]. Human factors in decision making, such as affect bias and the role of personal relationships, has been under-studied [16]. Similarly, the large effect sizes in these results might suggest students discount the value of personal relationships because they do not understand its role in process safety decision making, possibly due to a lack of experience with these types of decisions.

Tables 1 and 2 show there is a clear prioritization of the safety criteria among senior chemical engineering students. However, this may be unrealistic within professional practice given how some of the presented case studies, such as the Chevron Refinery fire or Pryor Trust Well blowout, showed an imbalance of safety criteria with other competing criteria. At the Chevron Refinery, it is possible production requirements influenced the decision to maintain operation once the leak had been identified [15]. Thus, student rankings on this reflection may not be accurate of their behaviors in the work environment. Research has shown that surveys and reflection results can be confounded with inaccurate responses, either intentionally or unintentionally. Intentionally, individuals may possess social desirability bias, causing them to behave or provide evidence that they align with the desirable results of the context [31]. The pre-reflection used in this study was given in the context of a senior design or process safety course that had planned to use CUP in their curriculum. As such, students may have felt obligated to rank safety as their highest priority to align with the context of the course. Unintentionally, individuals may wrongly predict their behavior with a phenomenon known as behavioral forecasting [32], [33]. Regardless of context, students may sincerely believe they hold safety as their priority but lose sight of this when immersed in complex work dilemmas. It is unclear to what extent these two confounds come into play in how students respond to the reflection due to a lack of further data. In either case, further evidence would only be able to be gathered by placing the individual in multiple different contexts where expected behaviors may be different or measuring their behavior within an actual process safety environment after completion of the ranking. The implication of this discussion is that the pre-reflection design may be limited, and further investigation would be required to truly gage how students prioritize safety with respect to other criteria.

Research Question 2

The second research question investigated as part of this study was, *how does senior chemical engineering students' prioritization of decision making criteria change after exposure to a virtual process safety decision making environment*? The Friedman test on the post-reflection rankings was found to be highly significant ($p<0.001$). This test on the post-reflection results suggest students are still perceiving certain criteria to be more important than others. A comparison between pairs of criteria from the post-reflection using a post-hoc Wilcoxon-sign-rank test is shown in Table 3 to determine which specific criteria students perceive as more important than others.

Table 3. Comparison between pairs of criteria rankings from the post-reflection using the Wilcoxon-signed-rank test and Cohen's d for effect size.

Criteria	P-value	Effect Size [29]
Budget - Personal Relationships	p<0.060***	0.35, small
Budget - Plant Productivity	p<0.001***	1.14, large
Budget - Safety	p<0.001***	3.01, very large
Budget - Time	p<0.001***	0.56, medium
Personal Relationships - Plant Productivity	p<0.001***	0.69, medium
Personal Relationships - Safety	p<0.001***	2.27, very large
Personal Relationships - Time	p<0.001***	0.88, large
Plant Productivity - Safety	p<0.001***	1.61, very large
Plant Productivity - Time	p<0.001***	1.70, very large
Safety - Time	p<0.001***	3.73, very large

During the pre-reflection students might have perceived budget and plant productivity to be similar criteria given the small effect size shown in Table 2 ($p<0.001$; Cohen's d=0.43, small effect). Yet, during the post-reflection, after the immersion with CUP*,* this is not the case where we see a decrease in the prioritization of budget while the average ranking of plant productivity stayed approximately the same shown in Table 3 ($p<0.001$; Cohen's d=1.14). In designing the reflection prompt, budget and plant productivity were differentiated because of the situations built into CUP. Budget was designed to account for spending decisions that impact the plant productivity meter in CUP. For example, when posed with a request from an employee to buy new gloves, the user may respond with: "There must be gloves we can borrow from another unit today." Whereas plant productivity was designed to account for labor decisions that impact the productivity meter in CUP. When posed with a request from an employee to join them for a lunch out, the user may respond with: "I'm not taking lunch today. I need to worry about preparing the plant." Through the students' experience with CUP, it is possible that they gained new perspectives on the nuances associated with these two competing criteria in process safety decision making. Based on the information currently available, it is not yet possible to understand the granular details as to why students perceive the importance of these two competing criteria to be so different after the intervention. Further qualitative analysis of students' perspectives on these rankings may provide additional insight but were unfortunately out of the scope of this immediate work.

To understand how each individual criterion changed, a paired t-test was performed. These results, along with effect sizes for pre- and post-reflections, are shown in Figure 4.

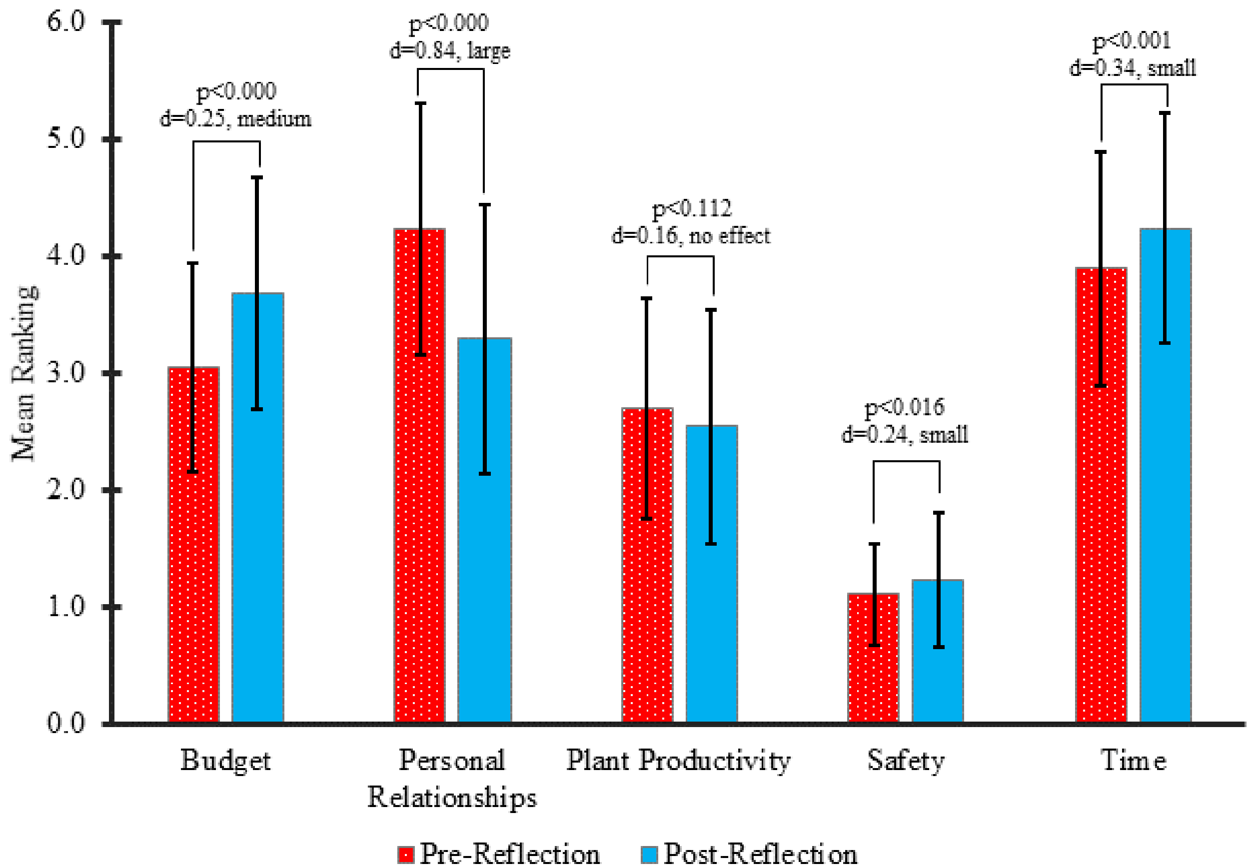

Figure 4. Pre- and post-reflection results compared using paired t-tests with p-value and Cohen's d effect size presented over each criteria's mean ranking and standard deviation error bars.

During the pre-reflection, personal relationships were ranked as the least important criteria. After the immersion with CUP, the paired t-test showed a highly significant increase in the prioritization of personal relationships with a large effect size. This suggests that exposure to CUP may have demonstrated to students how difficult it is to make process safety decisions when neglecting relationships with others. Friedman and Greehaus note that a balance between family and career might lead to the most satisfaction in life by increasing the capacity of self-fulfillment [34]. As such, Personal Relationships may have increased in importance because the students related it with satisfaction. CUP promotes acknowledging the importance of personal relationships through feedback to the user's choices. For example, the user may make the choice to stay late at work to create a hardworking image for their supervisor, but a feedback card may reveal staying late at work has led to them missing a dinner with their family. Situations like this help promote the balance between family and career satisfaction discussed by Friedman and Greenhaus [34]. The desire to uphold this balance may permeate into the working environment as seen with the role of affect bias in decision making [24]. The goal of CUP is not to force students into a predefined mold of priorities. Instead, CUP is designed to reveal the complexities of process safety decisions. In this case, the realignment of priorities shows students are acknowledging their initial evaluation of personal relationships may have under ranked its role, and it may not reflect that which they will hold in industry.

From the paired t-test, safety decreased in importance with a small effect size. Earlier discussion in response to Research Question 1 acknowledged that this prioritization may not always be the case, and the role of social desirability bias and behavioral forecasting in the ranking obtained is still unclear. As of now, we see students' prioritization of safety is largely unchanged, but further immersion could lead to other results. A previous study using CUP had found evidence of change in students' moral reasoning, but the extent of change was limited to the duration of the immersion [35]. If the duration of CUP is too short, then the intervention might not be authentic in capturing the complexities of decision making resulting from being occupied in the process industry over a longer term.

The goal for this study was to help senior chemical engineering students acknowledge the complexities associated with process safety decisions, which have competing criteria. As such, the current results demonstrate that immersion through exposure to CUP does modify how senior chemical engineering students perceive certain competing criteria in light of being faced with a more authentic representation of these decisions but does not yet explain fully why these changes may have occurred.

Limitations

This study consisted of approximately 200 senior chemical engineering students from three US institutions. The findings may be limited in that the sample does not capture differences in criteria prioritization associated with culture or country background. Thus, findings could differ if sampled in other cultural contexts. In addition, the CUP intervention is specific to the field of process safety and to chemical engineering students. These findings may not be generalizable to other industries because of the nature of the intervention.

Implications and Conclusions

Industrial processes commonly use preventative safety measures, but these are often inhibited by poor personal decision making. Unfortunately, mechanisms of process safety decisions are not widely studied in academia. Thus, this work aims to bolster chemical engineering education by understanding how senior chemical engineering students rank competing criteria within process safety decisions based on exposure to the CUP digital immersive environment. The results showed senior chemical engineering students heavily prioritized safety, which does not align with some of the decisions made in case studies highlighting process safety incidents. As a result, further studies should be done to investigate the role of social desirability bias and behavioral forecasting to gain insight on the sincerity of responses to the reflection prompts in CUP. Ranking results obtained after the immersion showed students perceived budget and plant productivity differently than prior to this experience. It is currently unclear why plant productivity was ranked as more important but further investigation will be done in the coming months. In addition, the results showed a significant increase in the prioritization of personal relationships after the CUP immersion. Without the immersive training, students may undervalue the importance of this criteria, but with immersive training, students may realize that personal relationships play a greater role in their decisions and may help them derive satisfaction from their work. This observation supports the use of CUP in process safety courses to help students acknowledge how complex decisions may be and that the priorities they hold as undergraduates may differ from those they may form once working in the process industry.

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