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Exploring Engineering Students' Decision Making Priorities in a Digital Plant Environment

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Introduction

Chemical process leaders recommend teaching process safety through case studies and hazard analysis [1]. While process safety textbooks and curriculum tools from the Safety and Chemical Engineering (SAChE) program [2], [3] prepare engineers with an awareness of the risks of the equipment they will work with, this approach can overlook the need to develop engineers' decision making abilities. Oftentimes, when educators use case studies, the case studies tend to be well structured, whereas real world dilemmas may be more complex without clear right and wrong answers. In addition, real world decisions often require engineers to make trade offs among critical criteria that are not always well represented within case studies. A failure to balance these criteria can escalate manageable process safety decisions into severe incidents that negatively impact the economy, the environment, and human well-being.

Great strides have been taken to assure engineers' preparedness for these real world dilemmas. For example, ABET-accredited programs require engineers to be able to make informed decisions that balance professional and ethical responsibilities [4]. However, current requirements leave out the complex array of criteria that engineers may truly weigh while making decisions. Recent fatalities at a flood station in Aghorn, Texas [5] highlight criteria, such as personal relationships, that may contribute to process incidents. However, engineers may have little trained experience in decision making involving such criteria. Thus, process safety education needs to include training on making decisions with criteria that may compete with best practices in safety. Before initiating training, we as educators need to understand how engineers are currently making decisions.

This study explores engineers' decision making priorities by examining their actual decisions in an immersive game context, *Contents Under Pressure*. *Contents Under Pressure* is a browser based, binary decision game specific to process safety. The immersive context of the game enables us to uniquely view engineers' behavior in an environment safe from actual plant hazards and separate from the engineers' predictions [6].

Process Safety

Chemical process engineers mitigate incidents and disasters through their decisions on a daily basis, and "the potential always exists for an accident of catastrophic proportions" [1, p. 38]. To fortify engineers' ability to mitigate incidents, prior incidents are studied for faults and pitfalls. One organization leading investigations is the US Chemical Safety and Hazard Investigation Board (CSB). Since the CSB's formation, they have investigated over one-hundred-thirty incidents and prescribed over eight-hundred recommendations for industry [7]. Despite these efforts, incidents continue to occur from incorrect operating procedures, equipment failure, and poor decision making [8]–[10].

Engineers tend to approach incident mitigation through a combination of two approaches: design [1], [11] and decision making. While both are critical to process safety, decision making can inhibit the effectiveness of safely designed equipment or protocols [12]. For example, the loss of life during the Pryor Trust well blowout did not result from faulty or inadequate equipment. Instead, major causes were traced to a series of poor decisions, such as muting safety alarms and performing a drilling procedure without training [9]. Educational responses to incident mitigation have been vigorous. ABET amended their desired outcomes to require chemical engineering students to be able to recognize ethical responsibilities and hazards within their work [4]. SAChE developed training modules and ethics case studies to be used in undergraduate classrooms [2]. However, additional training is still needed to address the prevalence of decision failures that lead to process safety incidents.

Role of Criteria

Chemical engineers are currently taught, in-part, by case studies that are contextualized and well-structured with easily identifiable hazards for classrooms. Yet, real world dilemmas are often ill-defined and include complex considerations [13], [14]. Such dilemmas may force engineers to make decisions that trade off criteria. For example, a leaking pipe at a refinery forced engineering managers to balance safety with demands for plant productivity. Shutting down production likely would have mitigated risks of the leak, but the engineers made the decision to keep the plant operating to maintain production while attempting repairs [15]. A striking number of CSB case studies provide evidence of trade offs among such criteria, but there is a gap in understanding the exact role that criteria play in process safety decisions.

Research Question

Literature shows an imbalance of decision criteria can create a pathway to process incidents. Some suggest safety should be a required consideration in all decisions [16]. However, this approach is obviously not the case in practice given the number of incidents that occur because the value of safety or other criteria were discounted while making decisions. As such, it is valuable to explore engineers' ability to balance and prioritize criteria in complex dilemmas. The research question guiding this work is *how do senior chemical engineering students prioritize process safety criteria as they make decisions in a digital game?*

Methods

This study was conducted in four ABET-accredited chemical engineering programs, sampling senior chemical engineering students from senior design and process safety courses. In each course, gameplay through *Contents Under Pressure* is regularly assigned regardless of participation in the study. Sampling led to collecting gameplay data on 185 students. We filtered game data for paragamers and as a part of a pairing procedure. Paragamers are those who play a game for the score by breaking immersion with the narrative [17]; they were filtered by game data that showed replaying days in the game, as multiple gameplays would suggest unrealistic awareness of future decisions and outcomes. The pairing procedure allows this sample to be included in a broader, multimethod analysis from multiple data sources. Following these two procedures, 82 students remained for the proposed analysis.

Contents Under Pressure

Authentic decision making is difficult to observe while in predictive and course based contexts. As a remedy, this study collects data through an authentic, immersive game known as *Contents Under Pressure* (Figure 1). *Contents Under Pressure* is a browser based game students complete outside of class as a homework assignment. Students roleplay as a new senior manager at a chemical processing plant over the span of 15 days of gameplay narrative. A single day of narrative lasts ten to twelve minutes covering about twenty decisions ranging from the mundane (assigning mop duty) to the critical (responding to chemical leaks). Decisions are binary where students may respond to dilemmas and coworkers by clicking one of two decision cards. Through their decision making, students must balance a series of metrics as the senior plant manager: time, reputation, safety, and productivity. The status of the latter three metrics is shown with emoticons on the top of the game screen. These emoticons are associated with hidden numeric scores. Hovering the mouse over either of the two decision cards previews which metrics will be impacted by their response by flashing the metric icons. Neglecting one of these metrics by obtaining the minimum score of (-100) triggers a game failure. This failure deducts points from the final game score, and the neglected metric is then reset to (-50). Time consumption varies for each decision, and this metric resets daily. The status for other metrics is carried in between days of narrative. Metric scores and decisions for each student are extracted from the *Contents Under Pressure* browser site using Google Analytics. Further description of *Contents Under Pressure*, including example gameplay, may be found elsewhere [18], [19].

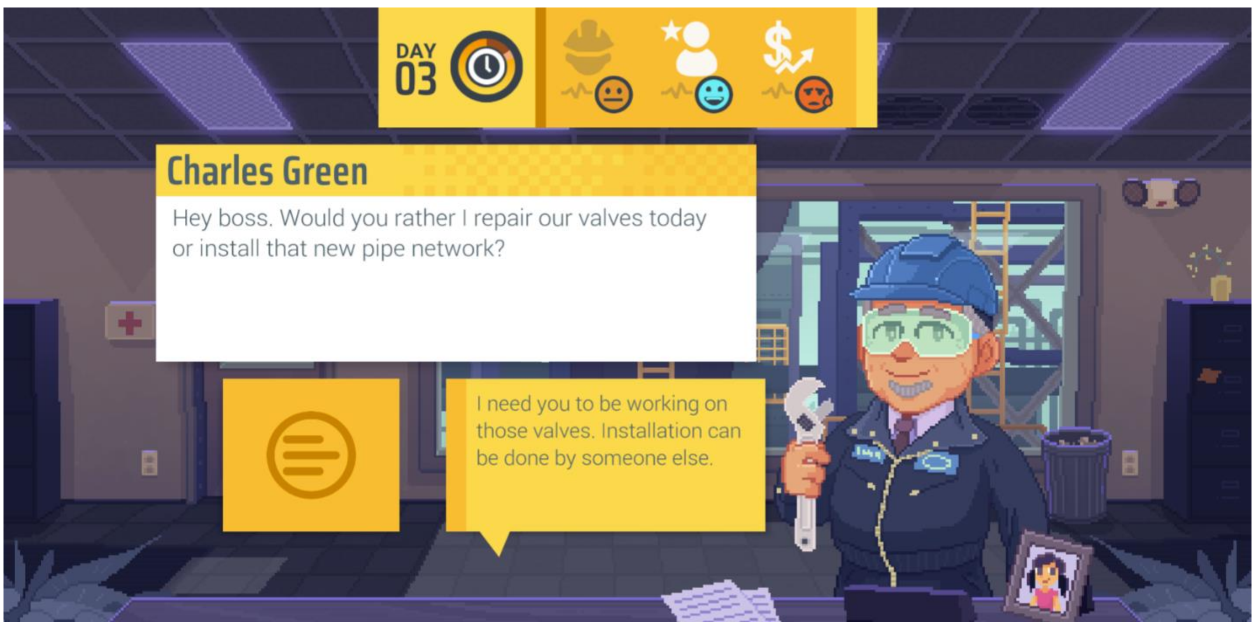

Figure 1. Screenshot of *Contents Under Pressure* game in browser window.

Time Series Analysis

The metric scores built into *Contents Under Pressure* potentially influence students' decisions per the game's objective to balance metrics. As the scores change from decision to decision, the metric scores are recorded for analysis. Metric scores over the course of the narrative create trends that are analyzed using time series analysis (TSA). TSA is typically used to find the effect of an intervention [20], but more recently, others have adapted the analysis to observe decisions and behaviors in educational games [21]–[24]. TSA of the game metrics (safety, reputation, and productivity) show trends and general perception of the represented criteria, and TSA of each student shows their priorities by the metrics' average scores and granular trade offs. Specifically, we use TSA to identify trends and highlight irregularities in the data [20], [25].

Results and Discussion

This study sought to answer *how do senior chemical engineering students prioritize process safety criteria as they make decisions in a digital game?* We observed through TSA that the safety metric was the top priority among students, and the reputation metric was a close second. We also observed that students may discount the value of the productivity metric as supported by the frequency of failures in this metric and negative mean time series.

The time series for the safety metric shows that all students in this study prioritized safety to an extent that the minimum score across 82 students was (-20). Also, safety's mean time series was positive with a tight standard deviation (Figure 2). Oftentimes, the safety score was at its maximum value of (100), meaning the metric was maximized by ***all*** students at some point in the game. About three-quarters of the way through the narrative, students encounter a hurricane that inherently takes a toll on the safety metric. The hurricane is seen in Figure 2 with the vertical line (I). This specific drop is not necessarily indicative of a trade off with safety but of some influence of the game narrative.

The time series for the reputation metric shows that 63 of the 82 students (77%) kept their reputation metric in the positive metric region for the entire game narrative, and none experienced a failure in this metric. While reputation's mean time series was always positive, it differed from the safety time series in that it had a broader standard deviation (Figure 2). The broader standard deviation banding suggests inconsistencies with how students prioritize reputation.

The time series for the productivity metric shows all students obtained a negative score at some point, and 65 of the 82 (79%) obtained a failure at least once. TSA (Figure 2) shows productivity was traded off with other criteria at multiple points. The vertical line (II) shows an example of where productivity was discounted for safety. This discounting is exemplified when the mean safety score increased while the mean productivity score decreased. Another line (III) shows where students favored productivity over safety and reputation. This preference is shown by the increase in the mean productivity score, the decrease in the mean reputation score, and slight decrease in the mean safety score. Finally, the rise in productivity over day fifteen is an inherent result of the narrative, not the students' decisions.

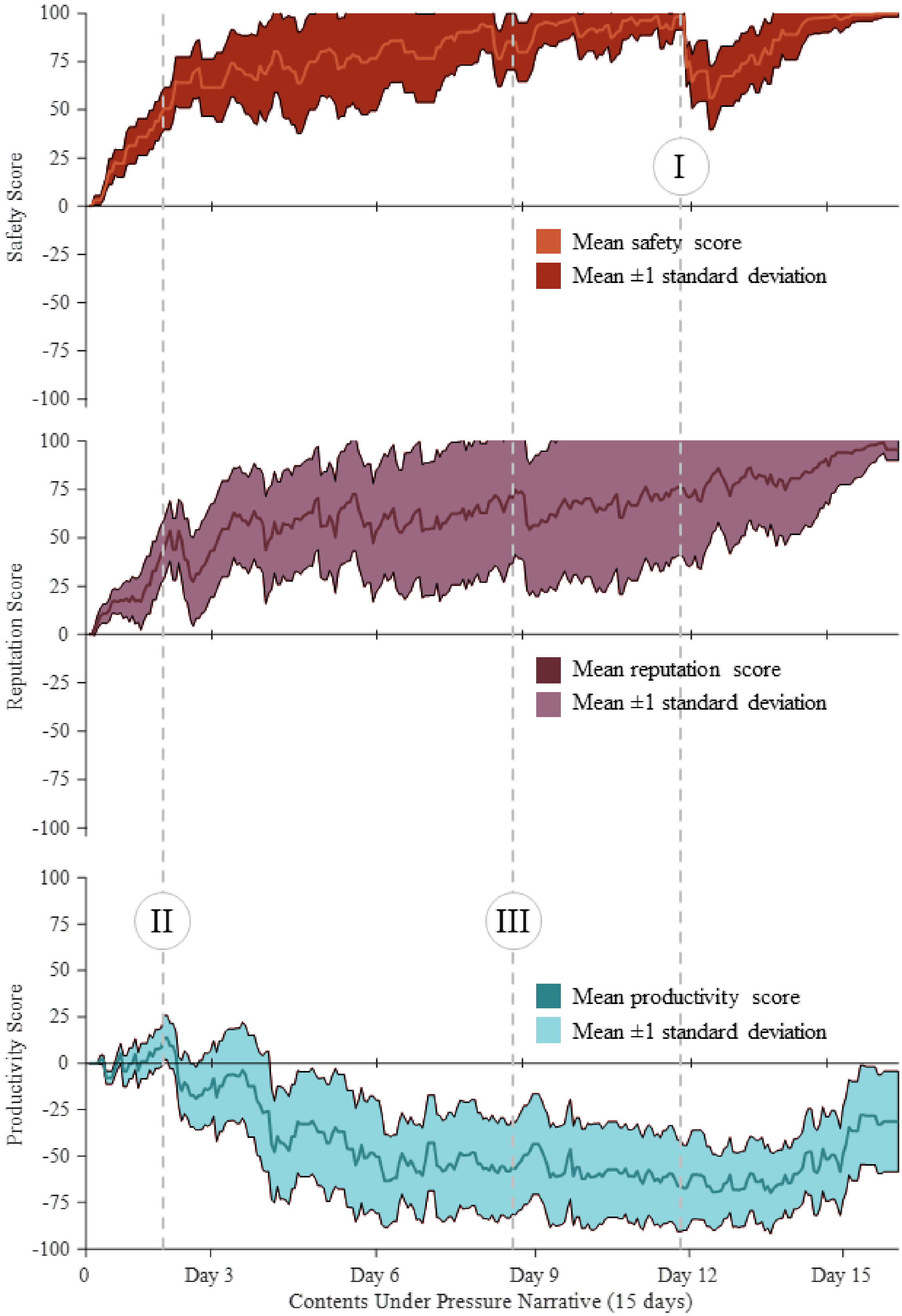

Figure 2. *Contents Under Pressure* metric scores for safety, productivity, and reputation.

Multiple dilemmas in *Contents Under Pressure* put safety in direct competition with productivity. One such case is when an employee identifies a minor leak, and the student must decide whether to ignore it (promoting productivity) or write up extensive reports to document the leak (promoting safety). In another case, an employee warns students of an approaching hurricane. The employee asks if they should switch to storm preparations (promoting safety) from their routine agenda (promoting productivity). Students were successful in balancing the game metrics in these decisions, but students did experience failures in the productivity metric in groupings over days with tropical storms (days four to six and days twelve to fourteen). In the game, students may respond to the storm by assigning employees to clean drain ways and place sandbags, which may take away from typical production deliverables. While the TSA suggested students generally discounted the value of productivity in favor of safety and reputation, the trade off seemed to be amplified during these storm dilemmas. Storm dilemmas may be unique in comparison to other types of decisions because there is adequate warning that a decision-critical dilemma is approaching. A major benefit of *Contents Under Pressure* over traditional process safety education methods is that it can promote authentic ethical fading [26] by hiding critical ethical decisions among mundane decisions [19]. Warning students of intense, upcoming storms may be a unique case where they overcome ethical fading.

TSA results show productivity trade offs with safety and reputation. Engineers approaching process safety decisions generally need to choose between promoting one criterion or another, suggesting an inverse relationship. This is similar to the aforementioned refinery fire [15]. However, this is not always consistent with other industries that rely on practitioner decision making. Multiple nursing studies have documented a relationship between patient care (safety) and hospital budget (productivity), where patient care declined when the hospital underwent financial pressure [27], [28]. A review of incidents in aviation found that poor management by air traffic controllers (leadership) can cascade into incidents for others in the aviation system, including the cockpit crew [29]. A civil engineering and construction management textbook points out that management's preliminary planning (time and leadership) can save on expenses (productivity) and promote safety throughout the project [30]. These examples support that relationships and trade offs exist among criteria that practitioners must consider. However, the exact relationships are likely nuanced at the industry level. Even within the discipline of engineering, civil and chemical engineers must consider the trade offs among criteria differently. Thus, this study begins to illustrate how senior chemical engineering students trade off criteria through their decision making. Additional work is needed to better define how engineers make and justify these trade offs to meet their priorities.

Recommendations

In an engineer's line of work, they must mitigate safety incidents, maintain professional relationships and their reputation, and meet work expectations such as production deliverables. Realistically, engineers must strike a balance among these criteria that compete for their time and attention. While process safety is inarguably critical for process engineers, engineers must still balance it with other criteria. Thus, our recommendation for chemical process instructors is to teach the need to balance multiple criteria when making process safety decisions and discuss the implications associated with making trade offs between the criteria.

Conclusion

Many chemical engineers enter industry without training in process safety decision making. Without training, they may be unaware of the complex trade offs in criteria that they must make through their decisions, which puts them at risk of undesirable process incidents. In an effort to improve process safety decision making education, this study sought to gain understanding on how students make these trade offs through an authentic decision making game, *Contents Under Pressure*. This study answered the guiding research question by finding safety and reputation were the prioritized criteria, followed by productivity, across the *Contents Under Pressure* narrative. The value of productivity may be particularly devalued in favor of safety and reputation in contexts where engineers are aware they are in high risk dilemmas. Decisions may rarely promote both safety and productivity, so chemical engineering education should continue to promote training in dilemmas with trade offs to strike a balance in avoiding safety incidents and failures in productivity.

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