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Assessing Embedded Process Safety Curriculum Within Core Chemical Engineering Courses

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Introduction

In a field that has been plagued by numerous industrial accidents and incidents since it's very beginnings, process safety education of chemical engineering students should be an important focus of every chemical engineering department's curriculum. To illustrate how important process safety education is, we only need to look at the number of industrial accidents in the recent past: the European Commission's Major Accident Reporting System (MARS) has logged over 129 major accidents since 1978 [1] while the U.S. Chemical Safety and Hazard Identification Board (CSB) has completed investigations of 105 accidents since 1998 [2]. These two databases only represent a portion of the larger number of incidents across the world and don't include smaller personal safety concerns like slips, trips, and falls.

As a result of major incidents such as the T2 Laboratories Inc. explosion in Jacksonville, Florida, the U.S. Chemical Safety Board (CSB) recommended that ABET include reactive hazard awareness to undergraduate chemical engineering curricula [3]. In general, ABET states that all engineering students should have "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors." Specifically, the chemical engineering curriculum should include "Engineering application of these sciences [math, chemistry, physics] to the design, analysis, and control of processes, including the hazards associated with these processes" [4].

While it is readily agreed that process safety education is important, there are many barriers to implementation, such as course overload in the chemical engineering curriculum, faculty knowledge on process safety, and student overload for additional external work. In a study published in 2016, only 23% of responding U.S. chemical engineering departments had a required process safety course [5]. Due to course overload in most chemical engineering curriculum plans, it seems ideal to integrate process safety within core chemical engineering courses [6]. However, implementation within core classes largely is based on process safety knowledge of faculty members or graduate student instructors. While the American Institute of Chemical Engineers' Center for Chemical Process Safety has developed many great tools including working with industry to facilitate the Faculty Process Safety Workshops, such as the one led by Bayer in October 2021 [7], considerable time and effort is needed to develop lecture material and/or homework problems. The incidents within the CSB and MARS databases can be a great tool to help students learn about how their chemical engineering knowledge can impact safety within the world, with the ultimate goal of minimizing future major accidents and incidents.

The SafeChE initiative [8] was started to provide faculty and students safety resources that can be more effectively and efficiently implemented throughout all chemical engineering courses. The website was launched by Professor H. Scott Fogler to increase the safety education of chemical engineering students throughout the world. As a result, it is free and accessible to all.

The primary type of resource provided on the SafeChE website are Safety Modules. These Safety Modules are based on various real-life industrial accidents investigated by the U.S. Chemical Safety Board [2] and are tailored for use in core chemical engineering courses. Other process safety educational resources can require more faculty overhead and multiple hours for students to complete and predominantly focus on educating students to Bloom's “understanding” level of thinking [9]. The SafeChE initiative Safety Modules require students to use an algorithmic safety analysis process to assess the incident, including initiating events, preventative actions, and contingency plans within the incident. The students are then asked to perform calculations and simulations based around the core chemical engineering course in which they are enrolled. Finally, students perform more advanced process safety analysis such as BowTie analysis, Hazard and Operability studies, and/or Layers of Protection Analysis studies. With the addition of the calculations, simulations, and analyses, the Safety Modules allow for more focus on higher levels of Bloom’s taxonomy of understanding, as well as linking safety principles and concepts to standard core chemical engineering theory and problems. As process safety consists of a complex range of topics, short tutorials are found on the SafeChE initiative site to also help faculty more easily integrate these Safety Modules into their course(s).

In this paper, we discuss the findings from an assessment done to determine the impact of students engaging with the SafeChE Safety Modules regularly throughout core chemical engineering courses. Specifically, a survey was created to determine if the Safety Modules achieved the following goals:

- Emphasizing how process safety is a professional obligation of a chemical engineer
- Increasing how often students think about safety
- Increasing student confidence in completing safety-related tasks

Students completed a pre and post survey before and after an academic year where they engaged with up to three Safety Modules throughout their courses. By comparing the pre and post survey, we can see the evolution of students' approach to and consideration of process safety and change in their confidence with completing various safety-related tasks.

Background

It has been shown in previous work that there is a positive correlation between a student's satisfaction with a task and whether they are intrinsically motivated to learn about that task [10]. Intrinsic motivation is defined as "the inherent tendency to seek out novelty and challenges, to extend and exercise one's capacities, to explore, and to learn" [11]. As a result, a study by Vigeant and Golightly [12] recommends building course attributes to take advantage of intrinsic motivation including topics such as real problems, topics focused on their career, and something that is personally meaningful. In order to leverage intrinsic motivation, the SafeChE initiative modules are built upon real industrial incidents that were investigated by the CSB. The expectation of the SafeChE initiative is that these real-world case studies will show students how knowledge they are obtaining in their current class can be applied to safety within a future career in industry. Also, since the CSB investigates incidents within the United States, some of our domestic students may study an incident that occurred "close to home".

Another aspect of a student that might drive their interest in learning about process safety is their perception of its importance in their future career. Based on interactions with students while teaching safety, the authors argue that student perceptions of the importance of safety within industry tend to differ from most industries' safety cultures. This discrepancy can be somewhat supported by a study of laboratory safety attitudes within academic, government, and industrial researchers [13]. In this study, self-reported PPE compliance behavior varied greatly between industry labs where compliance was higher than academic labs. Lab coat and eye protection compliance was 87% and 83% in industrial labs compared to 66% and 61% academic, respectively. While not all undergraduate students go directly to post-baccalaureate academic labs, many undergraduate students do. It is easy to assume that academia and industry have different safety training requirements, but this study stated that reported training was similar leading to a difference in safety culture and intrinsic motivation.

Methods

This paper presents the results of an assessment study done to determine the impact of integrating Safety Modules throughout the core chemical engineering curriculum. We analyzed student responses to a pre and post survey taken before and after an academic year where they engaged with various Safety Modules throughout their core chemical engineering classes, in order to determine how their approach to, perception of, and confidence with process safety evolved.

Participants

Table 1 summarizes the participants in this study, including the graduation year of the participants. Demographic data (such as gender, race, ethnicity, etc.) was not collected.

Table 1. Study participants

			Graduation Year			
Survey	**n (total)**	**n (completed survey)**	**2019 (Seniors)**	**2020 (Juniors)**	**2021 (Sophomores)**	**2022 (First-Year)**
Pre	102	52	23	12	16	1
Post	103	48	21	13	14	0

While over 100 students started each survey, only 52 and 48 students completed the entire pre and post surveys, respectively; only their data is analyzed here.

In the surveys, students were asked to create a 6-digit PIN (first three letters of their mother's first name, birth month numbers (i.e., 01 = January), and first letter of the city they were born in. This was intended to allow for comparison of exact student data from the pre and post surveys, without students needing to reveal their identity. However, only 18 students entered matching PINs for both surveys; so, rather than considering how each students' perceptions changed individually, we compared the two datasets as unmatched sets.

All of the participants were chemical engineering students engaging with the core chemical engineering curriculum. Over the course of the year, sophomores may complete Safety Modules in their material and energy balances, thermodynamics, and fluids courses. Juniors completed Modules in their heat and mass transfer, separations, and kinetics courses. Seniors might encounter Safety Modules in controls.

Data Collection

The pre survey was distributed at the start of the Fall 2018 term (in September 2018). The post survey was distributed at the end of the Winter 2019 term (April 2019). The survey was left open for approximately 4 weeks before being closed; for the pre survey, this timeline was selected so students would fill out the survey before encountering any Safety Modules in their classes. The survey took approximately 15-25 minutes for students to complete. At the conclusion of the survey, students could click an external link to log their name and email address; this entered them into a raffle to win a $50 gift card as incentive.

The assessment survey was written following best practices for survey development [14] and with the support of the Center for Research on Learning and Teaching in Engineering. The survey was developed to assess three main factors: how students perceive safety to be a part of their profession, how often students consider safety as a chemical engineering student, and their confidence in completing safety-related tasks.

The pre and post survey were identical. The survey data analyzed here consists of two parts:

1. **Working as a chemical engineer.** First, the students were asked open-ended questions about their responsibilities working as a chemical engineer. They were asked, as a new process engineer, what topics they would research to develop a new process, professional obligations they have when making decisions, stakeholders involved in the process, and challenges they have when considered safety.
2. **Current perceptions of ChE safety.** Next, the students were asked closed-ended questions about how often they consider safety as a student and their confidence level with completing different tasks related to safety.

Data Analysis

In this paper, we highlight findings from the two parts of the Safety Module assessment: analysis of open-ended responses to questions related to working as a chemical engineer and statistical analysis of closed-ended responses related to current perceptions of ChE safety.

In part one of the assessment survey, students were told that they were starting a new job as a process engineer. They were asked general questions about how they would approach their role. In this paper, we focus on the responses to two questions: “what are the first three topics that you research as you begin to develop your process?” and “what are three professional obligations you have when making decisions about the process?” Students were also asked to rank their responses to this question, where 1 is the most important topic/obligation and 3 is the least important of the three they mentioned. These two questions were chosen specifically to see how often students noted safety as a topic they would research or a professional obligation.

In part two of the Safety Module assessment survey, students were asked how often they consider safety throughout their chemical engineering education ("*How often do you think about chemical engineering safety in the following situations?")* and how confident they are in completing different safety-related tasks (*"How confident are you currently in performing the following tasks?").* For each set of questions, students answered questions along a Likert scale. For analysis, each Likert scale label was converted to a number between 1 and 5 (Table 2).

Table 2. Likert-scale items

	1	**2**	**3**	**4**	**5**
How often do you think about chemical engineering safety in the following situations?	Always	Most of the time	About half the time	Sometimes	Never
How confident are you currently in performing the following tasks?	Extremely confident	Somewhat confident	Neither confident nor unconfident	Somewhat unconfident	Extremely unconfident

Because we compared the pre and post survey data as two unmatched datasets (rather than matching data points based on the student PINs) we used T-tests (rather than paired T-tests), with a significance level of 0.05. We also used ANOVA testing to compare between graduation years.

Results

Changes in student perceptions of safety in chemical engineering

First, we will present the statistical findings from the second portion of the survey, comparing the pre and post values in student perceptions of how often they think about safety and how confident they are in completing safety-related tasks.

How often do you think about chemical engineering safety in the following situations?

There were no significant differences between pre and post values for how often students consider safety while working on chemical engineering work (Table 3).

Table 3. Changes in how often ChE students consider safety

	Pre	Post	Difference	P-Value
While doing ChE homework	1.82	2.00	0.18	0.228
While in ChE lectures	1.94	2.13	0.19	0.235
While studying for ChE exams	1.52	1.50	-0.02	0.899
While working on ChE projects	2.90	3.07	0.17	0.451
While in ChE lab	4.14	3.83	-0.32	0.171

It is interesting to note that there was a non-significant decrease in how often students consider safety while working in chemical engineering labs, particularly for junior and senior students (Table 4 and 5) who are the students enrolled in the lab during the year of this study. However, this decrease was not seen for sophomore students (Table 6).

Table 4. Changes in how often senior ChE students consider safety

	Pre	Post	Difference	P-Value
While doing ChE homework	1.82	1.95	0.13	0.571
While in ChE lectures	1.91	2.00	0.09	0.657
While studying for ChE exams	1.45	1.33	-0.12	0.577
While working on ChE projects	2.73	2.86	0.13	0.696
While in ChE lab	4.00	3.67	-0.33	0.291

Table 5. Changes in how often junior ChE students consider safety

	Pre	Post	Difference	P-Value
While doing ChE homework	1.83	2.00	0.17	0.544
While in ChE lectures	2.08	2.33	0.25	0.544
While studying for ChE exams	1.50	1.50	0.00	1

While working on ChE projects	2.92	3.33	0.42	0.388
While in ChE lab	4.50	3.67	-0.83	0.132

Table 6. Changes in how often sophomore ChE students consider safety

	Pre	Post	Difference	P-Value
While doing ChE homework	1.79	2.07	0.29	0.362
While in ChE lectures	1.93	2.14	0.21	0.458
While studying for ChE exams	1.69	1.77	0.08	0.849
While working on ChE projects	3.31	3.15	-0.15	0.689
While in ChE lab	4.25	4.30	0.05	0.913

How confident are you currently in performing the following tasks?

In considering how students' confidence changed in completing different safety related tasks (Table 7), there were general increases across most metrics, but no significant changes.

Table 7. Changes in how confident ChE students are in safety-related tasks

	Pre	Post	Difference	P-Value
Identifying elements of a process that could lead to a safety incident.	3.78	3.79	0.01	0.946
Identifying what risks are associated with different elements of a process.	3.61	3.89	0.28	0.102
Determining steps that can be taken to prevent safety incidents from occurring.	3.63	3.74	0.11	0.567
Determining potential hazards present in a plant.	3.78	3.77	-0.01	0.285
Identifying steps that could mitigate a safety incident after it has occurred.	3.55	3.77	0.21	0.963
Analyzing what events lead to a safety incident.	3.83	3.91	0.08	0.628
Determining an initiating event that leads to a safety incident.	3.65	3.77	0.11	0.52
Determining how chemicals may damage people, property or the environment.	3.94	3.94	0.00	0.989
Determining how to best safeguard a process to prevent harm to people, property or the environment.	3.69	3.68	-0.01	0.942
Identifying steps to reduce the potential of a safety incident from occurring.	3.55	3.83	0.28	0.129
Determining the root cause of a safety incident.	3.65	3.81	0.16	0.41
Determining the chemical properties of materials that have potential to damage people, property or the environment.	3.73	3.87	0.13	0.475

Determining potential hazards associated with a process.	3.73	3.91	0.18	0.32
Identifying risk inherent in a process.	3.76	3.72	-0.04	0.849
Identifying how a process presents risk to people.	3.76	3.91	0.16	0.422
Creating a contingency plan to prevent future safety incidents from occurring.	3.45	3.72	0.27	0.182
Identifying how a process would impact the environment.	3.69	3.74	0.05	0.816

However, when considering each class of students separately, there were significant differences that emerged: while there were no significant differences for junior or senior students (Tables 8 and 9), for sophomores, there was a significant increase in their confidence in "identifying what risks are associated with different elements of a process" and "determining the root cause of a safety incident" (Table 10).

Table 8. Changes in how confident senior ChE students are in safety-related tasks

	Pre	**Post**	**Difference**	**P-Value**
Identifying elements of a process that could lead to a safety incident.	3.86	3.81	-0.05	0.831
Identifying what risks are associated with different elements of a process.	3.73	3.86	0.13	0.588
Determining steps that can be taken to prevent safety incidents from occurring.	3.91	3.62	-0.29	0.247
Determining potential hazards present in a plant.	4.00	3.71	-0.29	0.323
Identifying steps that could mitigate a safety incident after it has occurred.	3.68	3.71	0.03	0.909
Analyzing what events lead to a safety incident.	3.86	3.95	0.10	0.701
Determining an initiating event that leads to a safety incident.	3.64	3.71	0.08	0.778
Determining how chemicals may damage people, property or the environment.	3.91	3.76	-0.15	0.636
Determining how to best safeguard a process to prevent harm to people, property or the environment.	3.73	3.52	-0.20	0.438
Identifying steps to reduce the potential of a safety incident from occurring.	3.50	3.67	0.17	0.531
Determining the root cause of a safety incident.	3.77	3.67	-0.11	0.699
Determining the chemical properties of materials that have potential to damage people, property or the environment.	3.86	3.76	-0.10	0.71
Determining potential hazards associated with a process.	3.77	3.71	-0.06	0.819
Identifying risk inherent in a process.	3.68	3.67	-0.02	0.958
Identifying how a process presents risk to people.	3.73	3.71	-0.01	0.963
Creating a contingency plan to prevent future safety incidents from occurring.	3.36	3.62	0.26	0.378
Identifying how a process would impact the environment.	3.68	3.67	-0.02	0.96

Table 9. Changes in how confident junior ChE students are in safety-related tasks

2020 GRADS	**Pre**	**Post**	**Difference**	**P-Value**
Identifying elements of a process that could lead to a safety incident.	3.75	3.50	-0.25	0.497
Identifying what risks are associated with different elements of a process.	3.75	3.83	0.08	0.823
Determining steps that can be taken to prevent safety incidents from occurring.	3.25	3.75	0.50	0.294
Determining potential hazards present in a plant.	3.58	3.67	0.08	0.874
Identifying steps that could mitigate a safety incident after it has occurred.	3.42	4.00	0.58	0.226
Analyzing what events lead to a safety incident.	4.00	3.83	-0.17	0.653
Determining an initiating event that leads to a safety incident.	3.83	3.92	0.08	0.79
Determining how chemicals may damage people, property or the environment.	4.08	4.08	0.00	1
Determining how to best safeguard a process to prevent harm to people, property or the environment.	3.67	3.67	0.00	1
Identifying steps to reduce the potential of a safety incident from occurring.	3.75	3.75	0.00	1
Determining the root cause of a safety incident.	4.00	3.75	-0.25	0.456
Determining the chemical properties of materials that have potential to damage people, property or the environment.	3.75	4.00	0.25	0.56
Determining potential hazards associated with a process.	3.75	4.00	0.25	0.499
Identifying risk inherent in a process.	3.92	3.82	-0.10	0.821
Identifying how a process presents risk to people.	3.83	4.00	0.17	0.707
Creating a contingency plan to prevent future safety incidents from occurring.	3.67	3.82	0.15	0.713
Identifying how a process would impact the environment.	3.58	3.64	0.05	0.905

Table 10. Changes in how confident sophomore ChE students are in safety-related tasks

	Pre	Post	Difference	P-Value
Identifying elements of a process that could lead to a safety incident.	3.64	4.00	0.36	0.285
Identifying what risks are associated with different elements of a process.	3.29	4.00	0.71	0.048 *
Determining steps that can be taken to prevent safety incidents from occurring.	3.50	3.93	0.43	0.272
Determining potential hazards present in a plant.	3.64	3.93	0.29	0.441
Identifying steps that could mitigate a safety incident after it has occurred.	3.50	3.64	0.14	0.702
Analyzing what events lead to a safety incident.	3.71	3.93	0.21	0.5
Determining an initiating event that leads to a safety incident.	3.57	3.71	0.14	0.687
Determining how chemicals may damage people, property or the environment.	3.93	4.07	0.14	0.669
Determining how to best safeguard a process to prevent harm to people, property or the environment.	3.71	3.93	0.21	0.574
Identifying steps to reduce the potential of a safety incident from occurring.	3.50	4.14	0.64	0.085
Determining the root cause of a safety incident.	3.14	4.07	0.93	0.023 *
Determining the chemical properties of materials that have potential to damage people, property or the environment.	3.57	3.93	0.36	0.318
Determining potential hazards associated with a process.	3.71	4.14	0.43	0.26
Identifying risk inherent in a process.	3.71	3.71	0.00	1
Identifying how a process presents risk to people.	3.79	4.14	0.36	0.355
Creating a contingency plan to prevent future safety incidents from occurring.	3.36	3.79	0.43	0.298
Identifying how a process would impact the environment.	3.79	3.93	0.14	0.664

* designates statistically significant difference at alpha of 0.05

Changes in student perceptions of a chemical engineer's responsibilities

This section presents the analysis of the open-ended responses in the first part of the survey, regarding students' perceptions of their responsibilities and obligations as a working process engineer.

What are the first three topics that you research as you begin to develop your process?

Table 11 presents the percentage of students who mentioned safety as a topic they would research before designing a process. A similar percentage of students ranked safety as the number one topic in the pre and post survey; however, many more students ranked it as second or third most important in the post survey. Overall, the percentage of students who mentioned safety at all more than doubled, from 23.5% to 52.0%.

Table 11. Changes in proportion of students ranked safety as a research topic

	Ranked 1	**Ranked 2**	**Ranked 3**	**Proportion of students who ranked safety in 1-3**
Pre	11.8	5.9	5.9	23.5
Post	12.5	25.0	14.6	52.0

What are three professional obligations you have when making decisions about the process?

In the pre survey, 63.5% of students considered safety in their top three professional obligations when designing a process; in the post survey, more than 85.4% considered it, most of them in their top-ranked obligation (Table 12).

Table 12. Changes in proportion of students ranked safety as a research topic

	Ranked 1	**Ranked 2**	**Ranked 3**	**Proportion of students who ranked safety in 1-3**
Pre	57.7	3.9	1.9	63.5
Post	66.7	16.7	2.1	85.4

Discussion

There were very few statistically significant changes, except for sophomores having an increased sense of confidence in two safety-related tasks (“identifying what risks are associated with different elements of a process” and “determining the root cause of a safety incident”). Because there were only significant changes for sophomores, this could imply that the Safety Modules work best when students are not also considering safety in more authentic contexts in their other courses (for example, being enrolled in a laboratory and/or design course) or when they are first being introduced to safety topics.

While the lack of statistical findings seems to imply that the Safety Modules did not significantly impact student perceptions of safety or their confidence in completing safety-related tasks, it must be noted that the analysis of the open-ended responses demonstrates a more positive finding. Before engaging with any safety modules, only 23.5% of students ranked safety as an important process design research topic. At the end of the year, more than 25% ranked safety as the number one most important research topic; 52% of students ranked it in their top three topics. Also, 63.5% of students ranked safety as a top three professional obligation at the start of the year; at the end of the year, 85.4% of students ranked it, with two-thirds of students ranking it as their number one obligation. Therefore, while we did not see many statistically significant differences in the quantitative metrics, it is clear that student perceptions of safety widened over the course of the year.

One specific finding that was interesting to the authors was the decrease in consideration of safety while in ChE labs for junior students (table 5). This was a non-significant decrease, but because it was one of the largest changes we saw in any metric, it is of interest of the authors to explore further. The 2019 cohorts would have gone through two (or possibly three) chemical engineering laboratory experiences, as the earliest a student can take the first chemical engineering laboratory course is typically in the winter of their junior year. Therefore, only some of the 2018 cohort would have taken a chemical engineering laboratory. It is unclear if students included their "Introduction to Engineering" laboratories in their considerations. Regardless, laboratory instructors had noticed the lowered focus on students with regards to safety within the chemical engineering laboratories and have since implemented additional process safety focused assignments within the labs such as mandatory weekly incident/near-miss reporting including focusing on actual risk and possible worst-case risk of the reported incident [15]. Implementation of more focused safety components to both improve safety culture and to expose students to process safety terms and experiences that they will most likely see in industry is an on-going process in the chemical engineering laboratories.

Conclusion

Incorporating process safety into the chemical engineering undergraduate experience can be challenging, given the already-packed curriculum with little room for new topics or courses. The SafeChE Safety Modules allow instructors to integrate safety topics throughout the curriculum, even in core courses where students may not be working in a laboratory or doing hands-on work. Quantitative findings demonstrated that sophomore students may benefit from the Safety Modules most in terms of increased confidence with safety-related tasks, but analysis of open-ended responses demonstrates that engagement with Safety Modules over the course of a year increased consideration of safety as an important element of being a chemical engineer.

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