A HAZOP TEACHING MODULE AND VERIFICATION STRATEGY FOR THE CHEMICAL ENGINEERING CAPSTONE SUBJECT

Colin A. Scholes
The University of Melbourne • VIC, 3010, Australia

INTRODUCTION

A HAZards and OPerability (HAZOP) study is a key safety analysis technique used by chemical engineers to identify and remove or minimize hazards within a process, as well as improve process effectiveness and efficiency.[1, 2] In industry, a HAZOP study is conducted by experienced engineers from different disciplines and career backgrounds in a group setting that follows a systematic manner to identify potential safety issues within a process. The identified safety issues are then evaluated for their severity and consequences to the process, with recommendations made regarding the process design as well as control and operation to eliminate or minimize the safety risk.

An important feature of any chemical engineering degree is the replication of a HAZOP experience for students as a vital tool in achieving learning outcomes in understanding process design, safety, and hazards considerations as well as evaluation of design options to minimize or mitigate risks.[3] In addition, the HAZOP provides students with the ability to draw on all their acquired knowledge, adapting the presented information to determine variation in operation status and interpret qualitative process outcomes to identify risks. This critical analysis has real-world relevance beyond a HAZOP study.[4] However, most chemical engineering programs give HAZOP a passing introduction, due to their complexity and time-consuming nature.[3] Furthermore, a detailed HAZOP is limited to senior/final year students due to the need for students to have a strong grasp of many chemical engineering concepts. As a result, a HAZOP is often added onto the capstone design project subject within a chemical engineering degree,[5, 6] taking advantage of the process design work undertaken by the students and building on safety and hazard learnings from prior subjects. In this manner, the students undertake HAZOP meetings to review process design drawings, control strategies, and operational procedures, using defined protocols to methodically evaluate the potential for the process to deviate from standard design operations. For those situations where deviation in operations is determined, the students then evaluate the risk of occurrence, the consequences of the deviation, and what actions might be taken to prevent this situation from occurring. As a result, the students take the HAZOP outcomes back to their design components and improve their process to operate more safely, replicating the actions arising from a real HAZOP.

Incorporating the HAZOP study as part of the capstone design project does create challenges that differ from having a dedicated HAZOP component in a prior subject. This is because the design project subject is intended to be strongly student driven, where students work in a team to develop a viable process design that depends on the students being self-motivated and having a major self-learning component.[5, 7] Hence, undertaking a HAZOP in such an environment without prior knowledge of how to analyze process designs for deviation from performance can lead to poor safety understanding. Compounding this is the expectation for students to self-organize unsupervised HAZOP meetings in the tight timeframe and pressures of their design project. One of the intended learning outcomes of HAZOP studies is for all students to partake in the meeting and gain experience

Colin A. Scholes *CChem FRACI CEng MIChemE is a Senior Lecturer in the Department of Chemical Engineering at the University of Melbourne. He is an expert in clean energy processing and membrane science, particularly developing strategies to assist the transition to a low carbon future. He is also a passionate engineering educator to people from disadvantaged backgrounds. He has worked with disadvantaged communities in Australia and the Pacific on sustainable water and energy projects.*

in the various roles, most notably chair and minute taker. Since meetings are unsupervised, there is the real possibility that certain students will not gain that experience. Unfortunately, the time constraint of the capstone design project as well as students being at different stages of their process design relative to their group members have resulted in several incidences where students mutually agreed not to hold a team HAZOP meeting. Rather, the students have undertaken an individual HAZOP of their own process, independent of other students, and submitted the result in the form of a standard HAZOP. This has meant the intended learning outcomes have not been achieved and can represent significant academic misconduct, given the students are in the final subject of their degrees.

Hence, this study presents a HAZOP teaching module as part of a design project capstone subject, designed to ensure that students achieved the study's intended learning outcomes, as well as a verification tool to establish that the group work component has been undertaken. The purpose of this study is to improve the teaching of HAZOP to chemical engineering students and verify that the intended learning outcomes are achieved for every student.

LITERATURE REVIEW

The teaching of HAZOP in the chemical engineering degree has been a core component since the late 1990s, associated with the rise in HAZOP in the chemical industry.[5, 8] Professional organizations, such as the Institute for Chemical Engineers (IChemE), have recommended institutions incorporate HAZOP components into multiple subjects in the degree as an approach to promote safety in design, with the capstone design project being a core part of this strategy. For additional learning there are also several short courses focused on HAZOP run by professional organizations that provide training for various roles in the process and the expectation of engineers undertaking a HAZOP.[9] The method in which HAZOP are presented to students varies considerably across institutions, although the professional organizations recommend that HAZOP teaching should be conducted to mimic the real process, involving teams of students. The great difficulty in teaching HAZOP is the need for the students to have a strong grasp of design principles as well as an understanding of the process unit(s) under review. To facilitate the learning, some institutions have developed animated teaching modules based around unit simulations that enable students to explore the outcomes of applying guidewords to process parameters, identifying hazards that arise within the simulation. In particular, the module developed at The Hong Kong University of Science and Technology has been well received by both students and educators.[3, 10] Similarly, the use of dynamic process simulations has been applied at Singapore Polytechnic with the same outcomes. The purpose of these computer simulations is to enable students to experience guideword outcomes and the generation of unsafe and hazardous conditions in a pre-established process. This combination of dynamic simulations with HAZOP procedures represents a strong learning tool for students.[11] However, these education tools do not replicate a real HAZOP, as an industry-based HAZOP has project engineers discussing outcomes and recommendations based on detailed design drawings and their experience without the presence of simulations tools. Hence, it is better to provide students with access to industry experience in hazard identification, which is achieved through mentoring the students through the HAZOP process. This is the reason why the teaching module presented here utilizes industry consultants.

A major component of HAZOP is the group discussion, as engineers raise points, analyze outcomes, critique responses, and approve recommendations among the group. Students undertaking HAZOP as a group achieve the same outcomes, as well as reinforce prior learnings and hold each other to account.[12, 13] Efforts to ensure that students have undertaken group work are limited in the literature, as most groups submit a joint piece of work for assessment. In the chemical engineering design project, students submit individual reports for assessment but with some sections, particularly the HAZOP, completed via group work. Ensuring the students have undertaken the work as a group is comparable to detecting collusion among students, where in this case detection ensures the learning objectives of the HAZOP have been achieved. There are a range of software tools available for the detection of plagiarism,[14] but collusion is generally harder to detect, as students rarely directly plagiarize each other. For mathematical assessments, collusion is generally identified through students providing the same answers in assessments as well as the same, or similar, procedure in deriving the answer.[15] For written assessments, collusion is generally identified through similar turns of phrases and references that are identified by educators. These distinguishing patterns in students' work can be quantified through various algorithms that scan student assessments for patterns.[16, 17] For a HAZOP, because of the specific nature of the activity, a more robust method of comparing students' reports is needed. Taking advantage of the HAZOP tables generated during the meetings can demonstrate group discussion and involvement.

RESEARCH DESIGN

The research objective is to evaluate the success of a dedicated HAZOP teaching module in achieving better safety in design outcomes as well as ensuring that students undertake all tasks associated with HAZOP learning. Strategies to ensure students undertake unsupervised HAZOP meetings are presented, with evaluation and commentary on their success. This verification tool, based on Zipf's law, enables educators to evaluate the reporting of HAZOP to determine if the work had been undertaken in a group forum. As such, the outcome of applying this analysis to student HAZOP reporting is provided with the objective of demonstrating the validity of the technique.

Intended Learning Outcomes (ILOs)

A design project capstone subject has many ILOs. These focus on students conducting process development and design, technology assessment, and integration; handling poorly defined design briefs in terms of process and technology options; and confirming final product state and purity. The specific ILOs associated with the HAZOP teaching module within the design project are as follows:

- carry out a preliminary HAZOP on specific process unit operations, as part of a team.
- conduct the roles and responsibilities of a HAZOP chairperson and team member.
- undertake the safety problem identification of unit operations.
- formulate a number of safety solutions for the identified problem.
- identify the most appropriate safety solution to implement.
- demonstrate independent thought and self-directed learning.
- conduct group critical thought with rational inquiry.

The objective of these ILOs is to ensure students gain a critical understanding of their process technology and identify unsafe and hazard operating conditions, resulting in the students evaluating the best solution to prevent or correct the situation. Students generally have a strong understanding of their process equipment and design prior to the HAZOP meeting, in part due to the wider design project requirements.[3] However, students generally struggle with formulating solutions to prevent hazard situations, in part because there are many potentially correct solutions, resulting in students over-designing their process and control schemes.

HAZOP Teaching Module

The HAZOP teaching module is run over a one-week period, during a 12-week semester. The module is generally conducted in week nine of the semester, when students have completed their detailed process and equipment design, designed their process control strategies and operating procedures, and constructed their piping and instrumentation diagram (P&ID). Hence, the timing of the module is chosen to provide guidance to students in the week before it is anticipated that they will need to conduct their HAZOP meetings (generally week ten). In this manner, the information is fresh in students' memories and easily referred to. Further details about the overall design project capstone subject structure, topic breakdown, and assessments can be found in the following reference.[5]

Lecture. The module starts with a 1-hour lecture that introduces the students to the general hazard aspects of a chemical process and what sections chemical engineers are responsible for in any plant relative to other types of engineering (e.g., mechanical and electrical). The lecture highlights major chemical plant incidents that have led to loss of life (e.g., Texas City refinery explosion and the Bhopal disaster), illustrating the consequences of failure to contain those hazards. Students are introduced to the difference between an accident and an incident, the importance of identifying the initiating event or circumstance, and following the chain of consequences. Concepts of safety in design are then presented in detail around accident prevention through:

- change in design
- change in process materials
- change in process conditions
- change in operation method
- improvement in integrity of safety systems

Major hazards with lower probability of occurring but with catastrophic consequences are discussed in terms of loss of containment and loss of control. This highlights equipment operating outside of design conditions, inventory overflow/underflow, incorrect operation, and loss of process control, topics that the students will encounter during their HAZOP. Other hazards with higher probability are also introduced, but due to lecture time limitations are not presented in detail.

Safety in design and the hierarchy of protection for design equipment (Figure 1) are then further reinforced, building on a teaching module undertaken earlier in the students' degree that looked specifically at process design. The importance of passive safety design is discussed because from experience, students favor active safety design; that is, students are more likely to address a HAZOP deviation through process controls, alarms, and shutdown systems rather than incorporate a passive design approach.

The HAZOP sequence is then introduced through the determination of a node around sections of a P&ID, the application of guidewords to process parameters, examination of possible causes, examination of consequences, listing existing safeguards, deciding upon actions, recording discussion, and decisions. The students are then shown a standard HAZOP meeting reporting table (Figure 2) that clearly has the guidewords present as well as the necessary divisions to answer because of considering those guidewords.

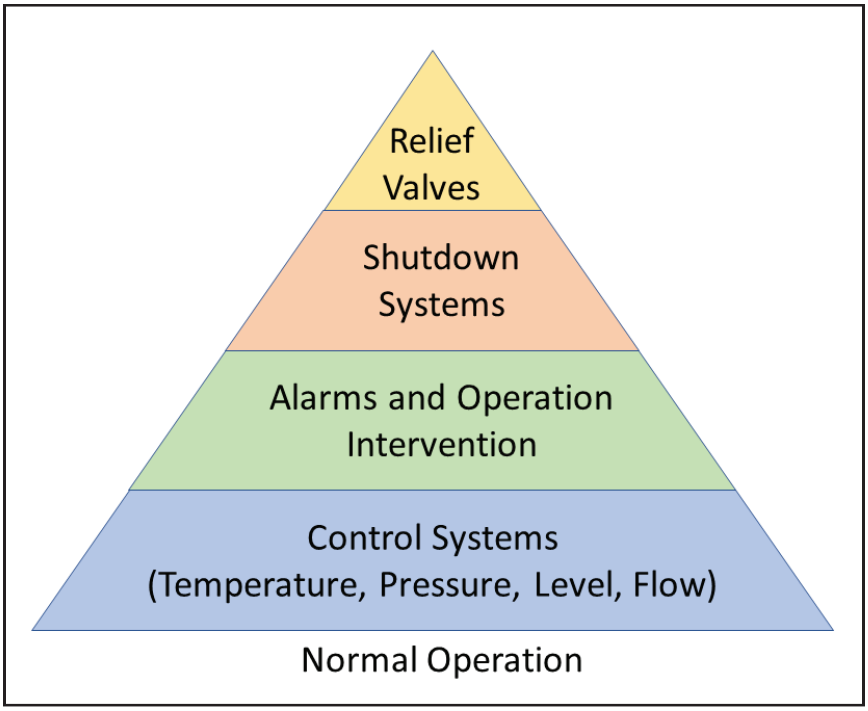

Figure 1. *Hierarchy of protection diagram used in the HAZOP teaching module.*

The lecture closes with a simple and short class exercise of a HAZOP on a steam-oil heat exchanger to demonstrate how nodes are chosen, the application of guidewords to the respective nodes, and process changes because of the outcomes (Figure 3). The timing of the lecture is based on introducing HAZOPs and highlighting their importance in industry (10 minutes), followed by the safety in design (10 minutes) and the HAZOP sequence (20 minutes). The simple HAZOP exercise closes out the lecture and generally takes ~20 minutes, dependent on the amount of student engagement. The lecture links the ILOs on carrying out a preliminary HAZOP, the roles and responsibilities of HAZOP team members, safety problem identification, and formulation of solutions.

Supervised Group Workshop. To follow up the lecture, each student design group spends 30 minutes in week nine of the semester with an industry consul-

HAZOP Report Sheet

Project:		Date:	Leader:
Design Intent:		PRESENT:	
Drawing No:		Page: 1 of	
Line No:		Hazop No:	

Hazop Actions Complete	**Sign**	**Indicator**	**Date**
Hazop Leader:			
Process Area/Department Manager			

#	Item	Deviation	Possible Causes	Consequences	Safeguards	Action Required	Actionee	By	Closeout Comments
	Overview								
	Flow	High							
	Flow	Low/Zero							
	Flow	Reverse							
	Pressure	High							
	Pressure	Low							
	Temperature	High							
	Temperature	Low							
	Impurities								
	Composition								
	Instruments								
	Testing								
	Startup checks								
	Operability								
	Electrical								
	Materials								
	Reliability/Simplicity								
	Commissioning/Startup								
	Breakdown, shutdown								
	Services								
	Effluent								

Figure 2. *Example HAZOP meeting reporting table.*

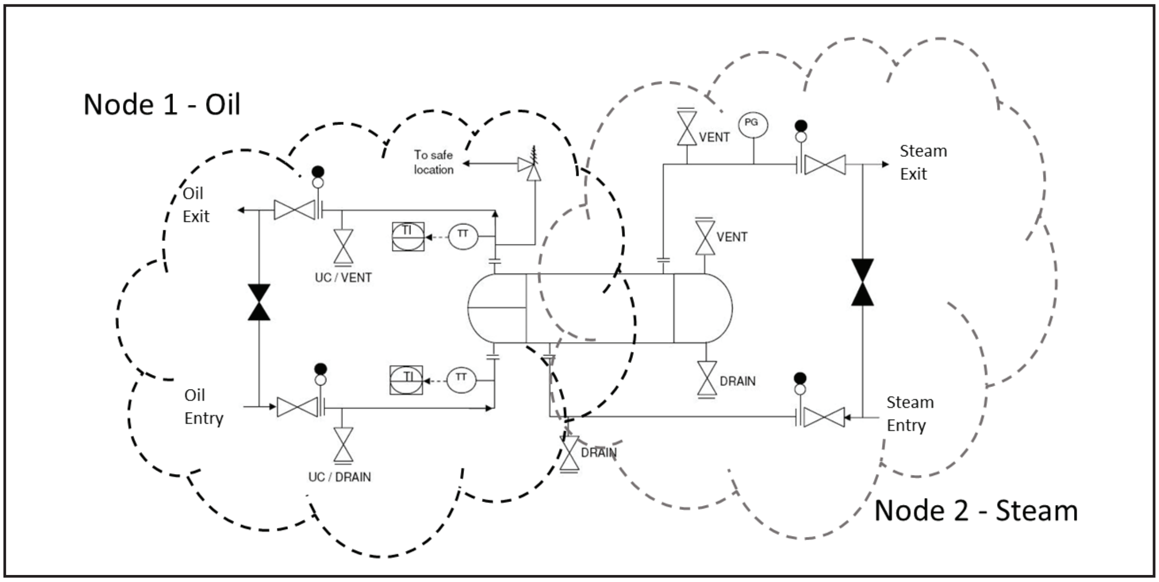

Figure 3. *Example a simple HAZOP on an oil-steam heat exchanger P&ID.*

tant to develop the HAZOP learnings further. Student groups consist of four or five students. The industry consultants are engineers who have experience and knowledge of the students' design topic. The consultants are paid for their time and specifically chosen for their knowledge of the design topic and process units under consideration. The consultants generally have at least ten years of industry experience, though some are semi-retired. This consultant session is part of the standard design project teaching, in that each student group must meet at least once a week with an advisor who helps them with their process design and works through problems with them.[5] However, in week nine the consultant session is a workshop focused specifically on the HAZOP and working through a mock meeting for one of the students' P&ID. The following key objectives must be achieved in this workshop:

- identification of nodes around a process P&ID
- establishment of an order of nodes to consider
- presentation of the control strategy and operational procedure for Node 1 by a designated student
- consideration of at least two parameters and all the guidewords for those parameters

The purpose of the consultant workshops is to give each student team a realistic experience of conducting a HAZOP guided by an industry advisor so that they understand the level of analysis needed for each parameter and guideword. This workshop also helps the students establish the likelihood of a safety issue and its possible consequences. The workshops are limited to only 30 minutes due to time and budget constraints, and it is not the expectation that the industry advisor will run the students' HAZOP for them. Rather, the role of the industry advisor is to talk the students through the potential for each parameter HAZOP guideword to occur, the possible causes, and resulting consequences, indicating the level of detail and analysis required as well as possible actions available. Guidewords include no or not, other than, more, early, less, later, reverse, etc., which are associated with the various parameters of the node. The workshop addresses the ILOs on identification of safety problems, formulation of safety solutions, and determining the most appropriate solution to implement, as well as reinforcing the ability to carry out a preliminary HAZOP. These are ensured through the discussion led by the industry consultant, who is instructed to cover these ILOs, with flexibility in the timing dependent on the student group's ability to achieve the individual ILOs in the session.

Student HAZOP Meetings Requirement and Reporting. As stated, the student groups are expected to self-organize their own HAZOP meetings and run them independently of the teaching staff following their supervised group workshop. The number of meetings is up to the students, but the group must ensure that each student fulfills the required roles and that all major process designs of the team have had a successful HAZOP undertaken. Generally, the students require a meeting per team member (e.g., four). To verify this has occurred, the students are asked, for each P&ID, to allocate a session chair and minute taker, and neither role can be filled by the student who designed the process under consideration. It is also expected that each student has a turn at being a session chair and minute taker, with the latter role being responsible for filling out the HAZOP meeting report table for the specific P&ID during the meeting. The students are then required to submit as part of their final design report the HAZOP reporting table of their specific process as well as the minutes of the meeting which they chaired.

An example of student HAZOP meeting minutes is provided in Figure 4 with the student names redacted. This enables comparison of student design reports, examining the HAZOP outcomes for their process as well as what is stated in the minutes of the student who chaired their process. This verification tool establishes that the student groups have undertaken a HAZOP meeting. The HAZOP reporting is designed to ensure that ILOs on formulation of safety solutions and identification of the most appropriate safety solution have been achieved. In addition, this tool verifies that the ILO on roles and responsibilities have been undertaken by all students and confirms that independent thought, self-directed learning as well as group critical thought ILOs have been met. These are corroborated through the minutes and the linking of the students' discussion among themselves and the decisions presented with the final HAZOP outcomes presented in their reports.

HAZOP Meeting Minutes

Attendees: [Students' Names]
Designer: [Student Name]
Date: 21/10/20
Time Commenced: 15:00 PM
Time Ended: 18:00 PM
Unit: Recrystallization: Crystallizer
Agenda:

1. [Student Name] explaining operation, existing process controls and nodes to team
2. HAZOP analysis of each node
3. Discussion of alterations and possible recommendations to minimize hazards in P&ID

Alterations to existing P&ID:

- Include fall close/open and reducers on all control valves
- Change CIP gate value to ball valve
- Include legends and notes in the P&ID
- Include a motor speed indicator as well as a motor stop alarm (MSA) in case motor fails
- Add manual globe valve to saturated steam stream for start-up and shut down purposes
- Ad flow transmitter and indicators to inlet feed streams to monitor flow from upstream process units
- Add pressure and temperature transmitter to saturated steam stream to monitor quality of steam from boiler process unit

Recommendations by team to consider:

- Incorporate surge control for outlet product stream pump to prevent the possibility of high pressure resulting in deviations of downstream flow
- To ensure riboflavin crystals produced are within the desired quality, consider adding a sample point at the outlet product stream for operators to retrieve crystallizer sample
- Remove the current guided wave level transmitter – place with the conventional displaced level transmitters as the HCl content in the solution may corrode the probe
- Venting of the crystallizer should be directed to a safe place just in case any HCl escapes
- Removal of flowrate control loop in the inlet to the crystallizer as well as for the deionized water as process is operating in a batch

Figure 4. *Example of student HAZOP meeting minutes, which is separate from the HAZOP reporting table.*

HAZOP Examples

The HAZOP teaching module has been applied over the past three years for several design project topics. The students submit their detailed design reports as individual assessments, with the HAZOP component included as a chapter in that report. The information provided in that chapter includes the group work component of the generated HAZOP reporting tables, marked-up P&IDs, and the minutes of the HAZOP meetings. Alongside this, the students provide an individual written component that describes the HAZOP outcomes for their individually designed major process unit and how the HAZOP has improved the safe operation of that unit.

The HAZOP meeting minutes (Figure 4) produced HAZOP tables and a written section on HAZOP in the students' final reports that demonstrated the teaching module ILOs had been achieved. The industry consultants also remarked that the level of safety issue identification, discussion, and analysis along with decisions improved notably in the years when the teaching module had been implemented.

Zipf's Law Analysis

To verify that student groups have undertaken a *group* HAZOP, rather than *individually*, an additional verification tool was applied: Zipf's law distribution analysis.[18] This law states that the frequency of any word is inversely proportional to its rank in a frequency table, and the law is associated with quantitative linguistics.[19-22] Essentially for any given body of written work, irrespective of language, the most frequent word will occur by some factor more often than the second most frequent word, which in turn will occur by the same factor more often than the third most frequent word and so on. This establishes an inverse power law based on 'r'th most frequent word having a frequency f(r) given by

$$f(r) \propto \frac{1}{r^a} \tag{1}$$

where 'a' is the power law exponent. For very large documents, 'a' approaches one and essentially demonstrates that the most frequent word is present at twice the rate of the second most frequent word and so on. For smaller documents 'a' varies dramatically but can be used to compare documents and establish fraudulent situations.[18, 23-25] This approach has been utilized here for analysis of the HAZOP reporting tables for students from the same group to help evaluate if a group HAZOP has been undertaken or students have instead done an individual HAZOP on their own process. The logic is straightforward; in a group environment the same key phrases will be used by students to describe outcomes from the guidewords, irrespective of the drawing under consideration.[26] These phrases are entered into the reporting tables for possible causes, consequences, safeguards, outcomes, and actions required for the various P&IDs and therefore the frequency of words will be very similar and specific words will dominate. As a result, the Zipfian frequency distribution would be very similar between the reported HAZOP reporting tables, denoted by the exponent 'a' and most frequent words used. Conversely, when students undertake HAZOP individually, there is not the same discussion and collaboration, and hence the resulting Zipfian frequency distribution may not be similar. The value of the Zipf's Law analysis is that it presents a rapid quantitative measurement of students' work in evaluating teamwork objectives and outcomes, rather than relying on educators' comparative judgement from reviewing reports.

It should be highlighted that the Zipf's Law analysis can only be applied to the HAZOP reporting table that is established during the HAZOP meeting and therefore written in a group environment. Additional discussion about the HAZOP undertaken by students, for example, describing the changes to the P&ID they have made because of the HAZOP should not be considered as this represents individual student work. Similarly, correlation does not equal causation, and a differing Zipfian frequency distribution does not in itself indicate that a student(s) undertook the HAZOP individually nor committed academic misconduct, but it does provide grounds for further investigation.

RESULTS AND DISCUSSION

Student Grades

The successful implementation of the HAZOP teaching module can be seen in the improvement in students' grades allocated to that section of the design project report after the module was introduced. These reports are graded independently every year and are given the following weighting for the various components:

- node determination on P&ID (10%).
- consideration of parameters, guidewords, and causes (20%).
- identification of parameters, guidewords, consequences, and actions (20%).
- determination of action items, including justification for refuting actions arising from guideword consequences (20%).
- evidence of change to process design, P&ID, control scheme and operating procedure because of the HAZOP (20%).
- successfully chairing a HAZOP meeting (10%).

This weighting strongly favors consideration of the guideword causes, consequences, and actions, as these demonstrate critical thinking in the students and a deep understanding of their process designs. The subsequent HAZOP grade distribution of students is provided in Figure 5, with a distinction between those students from years who did not undertake the HAZOP teaching module (six years of data) and those students who did (two years). There is separation in their performance, with the student cohort that undertook the HAZOP teaching module achieving higher grades (average of 77) than the student cohort that did not (average 71), with a less-distributed grading profile. The influence difficulty in design had on grade outcome was not considered a factor, as each student over the eight years of data designed for a unique process unit, and such variability in difficulty will average out in the large student cohort analyzed. The industry consultants holding a dedicated HAZOP meeting with the students, as part of the teaching module, was a large factor in the students' improved performance; however, industry consultants were also used for the student cohort that did not undertake the teaching module. Hence, the implementation of a dedicated meeting was the key component, rather than the presence of industry consultants. Direct feedback from the students on the HAZOP teaching module was not forthcoming in the university subject experience survey, which is conducted at the end of semester. Rather, students commented upon the overall teaching of the capstone design project subject, and therefore no impartial independent assessment of student opinions can be presented.

The markers of the student design reports provided feedback on the improvement in the HAZOP conducted by the students, in terms of the procedure presented by the students being more aligned with industry standards and the level of hazard analysis being comparable to graduate engineers.

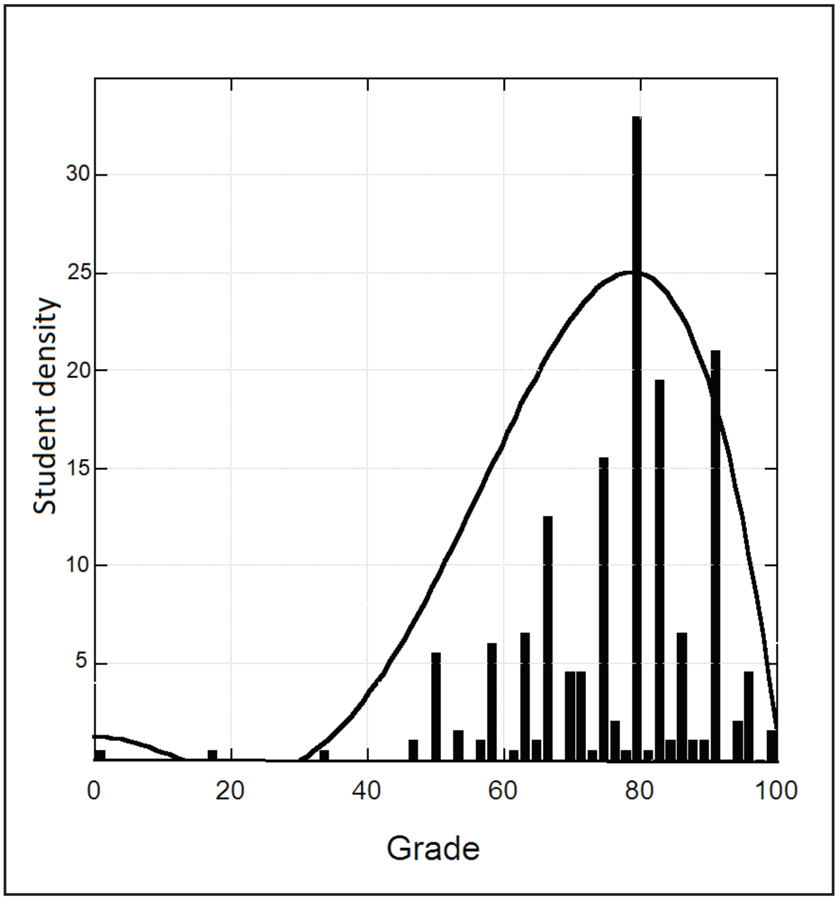

Figure 5. *HAZOP grades as a function of the student cohort who have undertaken the HAZOP teaching module (bars) and the previous years' student cohort who have not (solid line).*

Verification of Zipf Law Analysis

The Zipf law analysis of the students' HAZOP is a tool to verify that group work has been undertaken, as the underlying words and phrases used by the students are recorded in the resulting HAZOP reporting tables. Deviations in the Zipf law analysis between student members, in terms of the 'a' exponent and words most frequently used, may be an indication that students did not undertake the activity as a team. The analysis of HAZOP reporting tables first requires verification that the word frequency arising from the meetings follows a Zipf law's distribution, which is illustrated in Figure 6 for an example of a student's reporting table. For all student HAZOP tables, the word ranking and corresponding frequency strongly follows a power law distribution for the first ~40 words present within the reporting table, with an exponent of 0.595 determined for the example provided in Figure 6. The distribution does break down at larger word rankings, due to the HAZOP table being a brief document that has a lot of designation words, such as valve numbering, that are only used a few times in causes, consequences, or action items. Hence, the Zipf law analysis was limited to the first ~40 words of the HAZOP reporting table for comparison purposes.

To verify that Zipf law analysis can be used to assess group work in a HAZOP setting, two examples are provided in Tables 1 and 2 of a student group of five members and a group of four members who undertook HAZOP meetings observed by the author. It can be seen within each group that individual student's HAZOP reporting tables have 'a' exponents that are very similar, while the exponent between the two groups is different. Statistical analysis of students Zipf distribution exponents indicate student members within both groups are well correlated. This outcome is further supported by the predominance of the first three-word rankings from their HAZOP tables, with students demonstrating similar words and their ranking within both groups. Note, because the HAZOP tables are generally written in short statements rather than full sentences, common grammar articles that would generally dominate a Zipf distribution are present at higher word rankings.

Further verification of the approach is demonstrated by student groups that were known to the author not to have conducted a group HAZOP meeting, with Tables 3 and 4 providing the outcome of Zipfian distributions for two groups of five students, where the fifth student (E), due to special consideration, was granted an exemption to undertake their HAZOP individually separate from their group. For both groups, it can clearly be observed that the fifth student's HAZOP Zipf exponent differs from the other four students in their group. In Table 3, Student E's exponent is 0.612, compared to an average of 0.44 for the four students who undertook the HAZOP as group, which corresponds to student E's exponent being 5.3σ from the group's mean. In Table 4, Student E's exponent is 0.934, compared to the group's mean of 0.46, which is 14σ from the mean. These results indicate there is a statistically significant deviation in the Zipfian distribution for the student (E) who conducted their HAZOP separately from the group work. This is further supported by the prevalence of keywords in the distribution ranking, with the student (E) not sharing similar words with the other students in both tables.

A third example of a group not undertaking a combined HAZOP meeting is provided in Table 5, where a group of four students needed to be split into two groups of two

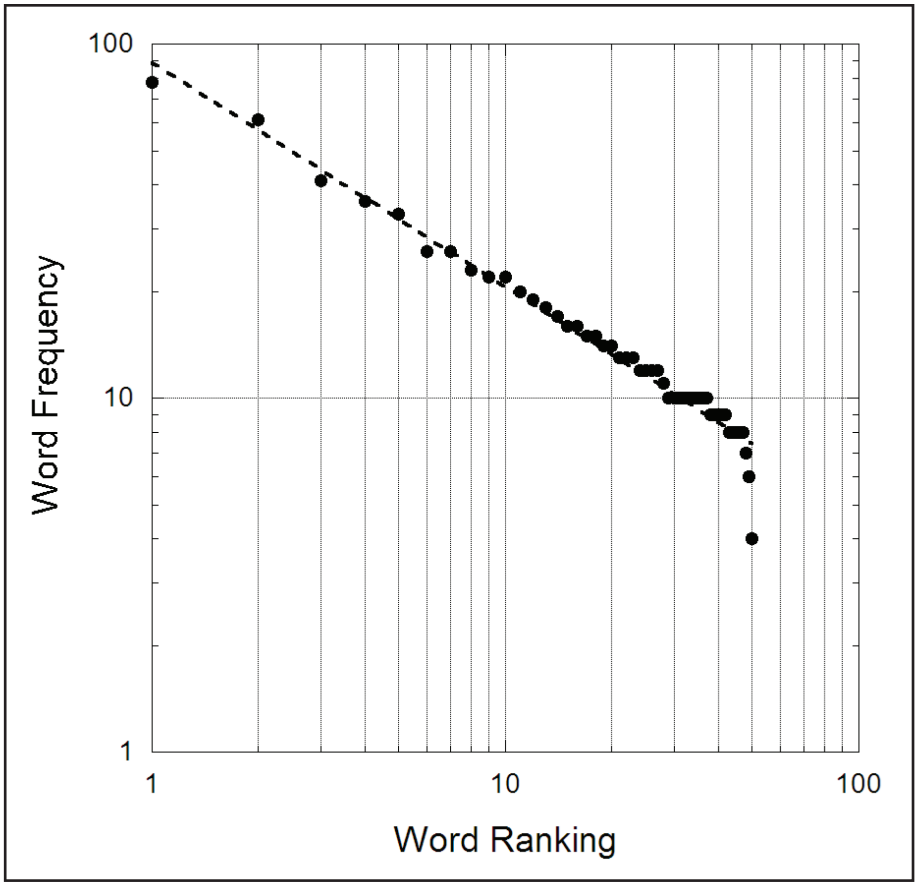

Figure 6. *Example of a Zipfian distribution analysis of a student's HAZOP reporting table.*

TABLE 1
Zipf distribution analysis of student group observed to undertake a HAZOP meeting in person.

Student	A	B	C	D	E
Exponent 'a'	0.308	0.350	0.358	0.380	0.370
1st Word	None	None	Flow	Control	Low
2nd Word	Same	Same	Low	Flow	None
3rd Word	Pressure	Temperature	Temperature	Low	Temperature

TABLE 2
Zipf distribution analysis of student group observed to undertake a HAZOP meeting in person.

Student	A	B	C	D
Exponent 'a'	0.443	0.437	0.407	0.427
1st Word	Pressure	Pressure	Regular	Flow
2nd Word	Flow	Flow	Maintenance	Operation
3rd Word	Add	Add	Pressure	Maintenance

students midway through the semester due to antisocial behavior among team members (A and B separated from C and D). The resulting Zipf analysis indicates that A and B students have very similar exponents and key words, implying that they worked together on their HAZOPs. In contrast, C and D students have different exponents from each other and from students A and B. This demonstrated that the two student groups split from the original group produced different HAZOP phrases from each other, even though they were analyzing the same overall process. Furthermore, the exponent difference between C and D students suggest they undertook their HAZOP individually. This is supported by the lack of keyword similarities between students C and D.

An example of Zipf's law exposing HAZOP academic misconduct is provided in Table 6 for a group of five students who have very different exponents that lack statistical similarity, and the keywords differ significantly among the five students. When approached by the author, these students admitted to having undertaken their HAZOP individually, with no input from their fellow team members, due to time limitations during their design project. Hence, this outcome demonstrates that Zipfian distribution analysis can be applied to chemical engineering student HAZOP meetings reporting as a tool to verify group work has been undertaken and ILOs achieved. However, before Zipfian distribution analysis can be widely adopted as a verification tool, more statistical analysis must be undertaken on a large data set of HAZOP reporting tables so that the level of deviation in exponent and keyword distributions that indicate individual rather than team activity can be identified.

TABLE 3
Zipf distribution analysis of HAZOP reporting tables for a student group where student E undertook their HAZOP separately as an individual.

Student	A	B	C	D	E
Exponent ‘a’	0.427	0.488	0.419	0.424	0.612
1st Word	None	Pump	Fermenter	Stream	Required
2nd Word	Pump	Installed	Control	Control	Action
3rd Word	Control	Control	None	Loop	Pipeline

TABLE 4
Zipf distribution analysis of HAZOP reporting tables for a student group where student E undertook their HAZOP separately as an individual.

Student	A	B	C	D	E
Exponent ‘a’	0.500	0.477	0.422	0.459	0.934
1st Word	Control	See	Flow	See	High
2nd Word	See	High	See	Level	Gas
3rd Word	Pressure	Reflux	High	Pressure	Alarms

TABLE 5
Zipf distribution analysis of HAZOP reporting tables for a student group where students A and B were instructed to work separately from students C and D.

Student	A	B	C	D
Exponent ‘a’	0.408	0.352	0.129	0.611
1st Word	Pressure	Indicator	Closed	None
2nd Word	None	Flow	Required	Valve
3rd Word	Indicator	None	Flow	Pressure

TABLE 6
Zipf distribution analysis of HAZOP reporting tables for a student group who conducted the activity individually.

Student	A	B	C	D	E
Exponent ‘a’	0.498	0.470	0.241	0.305	0.616
1st Word	Control	Required	Air	Valve	None
2nd Word	Temperature	Action	None	None	Pipe
3rd Word	None	Water	Installed	Flowrate	Boiler

Implementation of Zipf Law Analysis

There exist freely available algorithms that will construct Zipf law distributions for written text that can be utilized for the analysis presented here. These algorithms are generally associated with the marketing industry rather than engineering but have reasonable compatibility with engineering text, based on the author’s experience. These algorithms can readily be adapted to analyze student reports, but linking the HAZOP text with the underlying code and presenting the resulting distribution will require an interface to be constructed. For the analysis presented here, this was achieved by the author through their own code. The comparison of the Zipf law exponent and distribution table will be the task of the educator, as the data set is not sufficiently large enough to quantitatively establish when individually HAZOP have been undertaken. Ideally, Zipf law analysis will be implemented in academic software, such as Turnitin™, that is already designed to detect academic misconduct, such as plagiarism. These software tools access large databases of student work and therefore can more readily construct Zipf distribution parameters and identify deviations from them. This will bring additional utility to these software packages, as Zipf law distribution can be another technique to identify collusion among students, which for many assessment situations is serious academic misconduct.

CONCLUDING REMARKS

The teaching of HAZOP principles to chemical engineering students is a vital component of their degree, and the teaching module presented here focuses on ensuring that the ILOs are successfully implemented. The outcome is chemical engineering graduates who better understand HAZOP and the importance of hazard analysis and safety in their profession. A key component is the incorporation of the HAZOP into the design project capstone subject of the students, taking advantage of their considerable prior design work and understanding of their process. The combination of a lecture followed up with a workshop supervised by an industry advisor ensures the students gain a greater understanding of HAZOP requirements, as evidenced by an improvement in the students' grades for this component of their design project. The expectation for students to conduct their HAZOP in a self-organized group setting does present a challenge for educators, especially in identifying that all ILOs have been achieved. There is a tendency for students to avoid group work and undertake the HAZOP as an individual if they are under time pressures or are behind fellow group members in the progress of their section's process design. Hence, this prevents the full learning associated with HAZOPs from being achieved. However, to prevent an individual HAZOP, it is necessary to confirm collusion among the students in their presented reports. The Zipfian distribution analysis of HAZOP reporting tables arising from students' meetings represents a verification tool that can be used to establish that a group HAZOP has occurred. The frequencies and specific words between student members' HAZOP tables result in similar Zipfian distributions and therefore presents a method to establish that the students worked together as a team on their HAZOP. Student reporting tables that deviate from their fellow group members under Zipfian analysis may indicate that a group HAZOP was not undertaken. Instead, students undertook the process in smaller groups or as individuals. This is the first verification tool tested for student HAZOP analysis and presents a new approach to analyze student group work, when one of the ILOs is group critical thinking and student-led self-learning. However, more statistical analysis of a larger data set of student HAZOP needs to be undertaken to establish the parameters that can be used to verify the difference between a group and individual outcome. To conclude, the teaching of HAZOP ILOs to students is of vital importance for the profession, and verification that students have learned these ILOs is an ongoing challenge to educators. The teaching module and Zipfian distribution strategy presented are procedures to achieve this objective.

REFERENCES

1. Crawley F, Preston M, and Tyler B (2008) HAZOP: Guide to best practices. *Guidelines to Best Practice for the Process and Chemical Industries*. IChemE: Rubgy, UK.
2. Kletz TA (1999) *Hazop and Hazan: Identifying and assessing process industry hazards*. Taylor & Francis, Philadelphia, PA.
3. Noakes N, Chow CCI, Ko E, and McKay G (2011) Safety education for chemical engineering students in Hong Kong: Developoment of HAZOP Study teaching module. *Edu. Chem. Eng.* 6: e31-e55.
4. Burkholder E, Hwang L, and Wieman C (2021) Evaluating the problem-solving skills of graduating chemical engineering students. *Edu. Chem. Eng.* 34:68-77.
5. Scholes CA (2021) Chemical engineering design project undertaken through remote learning. *Edu. Chem. Eng.* 36:65-72.
6. Kentish SE and Shallcross DC (2006) An international comparison of final-year design project curricula. *Chem. Eng. Ed.* 40:275-280. https://journals.flvc.org/cee/article/view/122494 Accessed May 24, 2022.
7. Pekdemir T, Murray K, and Deighton R (2006) A new approach to the final year design projects. *Edu. Chem. Eng.* 1: 90-94.
8. Dunjo J, Fthenakis V, Vilchez JA, and Arnaldos I (2010) Hazard and operability (HAZOP) analysis. A literature review. *J. Hazardous Materials*. 173:19-32.
9. IChemE. On-demand online courses. www.icheme.org/career/training/on-demand-online-courses. Accessed May 16, 2022.
10. McKay G, Barford JP, Hui CWD, and Bazargan A (2014) Teaching process safety - Development of a HAZOP study teaching module. *Proceedings of the 2014 International Conference on Industrial Engineering and Operations Management*. Bali, Indonesia.
11. Eizenberg S, Shacham M, and Brauner N (2006) Combining HAZOP with dynamic simulation - Applications for safety education. *J. Loss Prevention in the Process Industries*. 19: 754-761.
12. Davies WM (2009) Groupwork as a form of assessment: Common problems and recommended solutions. *Higher Education*. 58: 563-584.
13. Michaelsen LK, Parmelee DX, Hyderi A, and Sweet M (2005) Team-based learning: Overview and best evidence. *Evidence-Based Education in the Health Professions*. CRC Press. 302-319.
14. Halak B and El-Hajjar M (2019) Design and evaluation of plagiarism prevention and detection techniques in engineering education. *Higher Education Pedagogies*. 4: 197-208.
15. Ercole A, Whittlestone KD, Melvin DG, and Rashbass J (2002) Collusion detection in multiple choice examinations. *Medical Education*. 36: 166-172.
16. Lyon C, Barrett R, and Malcolm J (2004). A theoretical basis to the automated detection of copying between texts, and its practical implementation in the Ferret plagiarism and collusion detector. *Plagiarism: Prevention, Practice and Policies Conference*. New York, NY.
17. Cleophas, C, Honnige C, Meisel F, and Meyer P (2021) Who's cheating? Mining patterns of collusion from text and events in online exams. *Informs Transactions on Education*. 10.1287/ited.2021.0260.
18. Bolton RJ and Hand DJ (2002) Statistical fraud detection: A review. *Statist. Sci*. 17: 235-255.
19. Dahui W, Menghui L, and Zengru D (2005) True reason for Zipf's law in language. *Physica A: Statistical Mechanics and its Applications*. 358: 545-550.
20. Rapoport A (1982) Zipf's law re-visited. *Quantiative Linguistics*. 16: 1-28.
21. Moreno-Sanchez I, Font-Clos F, and Corral A (2016) Large-scale analysis of Zipf's law in English texts. *PLOS ONE*. 11: e0147073.
22. Pietronero L, Tosatti E, Tosatti V, and Vespignani A (2001) Explaining the uneven distribution of numbers in nature: The laws of Benford and Zipf. *Physica A: Statistical Mechanics and its Applications*. 293: 297-304.
23. Huang SM, Yen DC, Yang LW, and Hua JS (2008) An investigation of Zipf's Law for fraud detection. *Decision Support Systems*. 46: 70-83.
24. Odueke A and Weir GRS (2012) Triage in forensic accounting using Zipf's Law. I*ssues in Cybercrime, Security and Digtal Forensics*. University of Strathclyde Publishing. Glasgow, Scotland. 33-43.
25. Piantadosi ST (2014) Zipf's word frequency law in natural language: A critical review and future directions. *Psychon Bull Rev*. 21: 1112-1130.
26. Mohammadi M (2016) Parallel document identification using Zipf's Law. *Proceedings of the Ninth Workshop on Building and Using Comparable Corpora*. Portoroz, Slovenia. LREC 2016, 21-25. ❐