Reflections on inherently embedding safety teaching within a Chemical Engineering programme

Michaela Pollock[1] and Eva Sorensen

Department of Chemical Engineering, UCL, Torrington Place, London, WC1E 7JE, United Kingdom

[1]Corresponding author: m.pollock@ucl.ac.uk

Abstract

The importance and the challenges of teaching safety are widely recognised amongst educators and industry. There are different approaches to teaching safety, from incorporation of safety into every aspect of a degree programme, to focusing all the safety teaching within stand-alone courses, to an integrated approach which simultaneously combines both approaches to varying extents. Effective safety teaching is also dependent on the experience and knowledge of the teaching staff involved and the locational context of the institution. Here, the novel and comprehensive approaches taken to inherently embed safety teaching within a chemical engineering programme, which is part of the wider Integrated Engineering Programme (IEP) teaching framework at UCL's Faculty of Engineering Sciences, are examined and its success is measured against student perceptions. Students following the IEP chemical engineering degree programme widely recognise that safety teaching is immediately embedded into the curriculum from the first year and they are given increasing opportunities to apply safety learnings throughout their degree. This leads to a feeling of preparedness for their capstone design projects and future industrial roles, ultimately achieving the aim of developing well-rounded, responsible graduate engineers with a strong safety culture embedded in the way they will approach their future work.

Highlights

- Examine challenges and approaches to safety teaching in an academic environment.
- Approaches are stand-alone course, include in all programme aspects or mix of both.
- Show how safety teaching inherently embedded in UCL's chemical engineering programme.
- Consider student perceptions for two cohorts taught based on different approaches.
- Student perceptions show feeling of preparedness for design projects and industry.

Keywords Teaching, Safety, Embedded learning, Chemical engineering, Integrated Engineering Programme, Student perception

1. Introduction

Safety is widely acknowledged as a fundamental and significant life-long area of learning and responsibility of chemical engineers. The aim of both educators and industry is to develop safety-aware, responsible and well-rounded chemical engineers. It is easy to understand how these aims can be achieved in an industrial setting where graduate engineers are solving real-life problems as part of experienced interdisciplinary teams, and are continually building upon their fundamental knowledge. However, for educators within the confinements of the classroom, where students have limited, if any, industrial experience and where they are still developing their core chemical engineering knowledge; it is challenging to effectively impart a strong awareness and appreciation of safety that can be built upon in an industrial role.

The significance of safety as a key learning outcome within an educational context is further reinforced by accreditation bodies. The Institution of Chemical Engineers (IChemE) (IChemE, 2020) require graduates to have gained an understanding of a variety of process safety learning outcomes through formally taught safety courses, as well as being instilled with an appropriate attitude to safety, health and the environment (SH&E). Departments must demonstrate an effective SH&E

culture with an appreciation and practice of SH&E embedded into the teaching, coursework and project work, and wider in terms of the general operation of the department. Equally, in the USA, ABET (ABET, 2020) states that the curriculum must include considerations of the hazards associated with the design, analysis and control of chemical, physical and/or biological processes. How these open-ended and broad-ranging learning outcomes on safety can practically be incorporated into a chemical engineering programme, however, vary.

Mannan et al. (1999) capture this problem through the quote "The challenge is how to create a culture in which consideration of process safety issues is second nature, driven by a total understanding of the underlying engineering, process chemistry, and other factors." The authors go on to propose that universities should provide an integrated engineering education that covers classical engineering fundamentals as well as providing an understanding of process safety. Mannan et al. (1999) suggest that this does not mean the development of a new discipline but rather the fine tuning of the existing engineering curriculum. Further to this, Pitt (2012) considers what is important in terms of what, how and who can teach process safety in chemical engineering in both academic and industrial contexts. He suggests that while students may easily learn how to perform release rate and dispersion calculations, it is much more challenging for them to solve open-ended problems, and equally it is difficult for educators to assess how well students have dealt with these open-ended problems.

There have been a number of works recently that have provided an overview of process safety and process safety education. Tanjin Amin et al. (2019) present a complete and rigorous bibliographic review of the evolution of process safety and risk research including brief comments on process safety education. A comprehensive study of safety teaching and engineering risk management is presented by Meyer et al. (2019) who examine process safety education as a detailed illustrative example. Their considerations include a range of perspectives such as accreditation, teaching strategies for process safety in different contexts such as academia, industry and authorities, as well as the types of process safety training that can be provided such as skills-based, mentoring or web-based. They extend their work by presenting examples of safety focused university MSc programmes including process safety management. Similarly Mkpat et al. (2018) perform an extensive review of process safety education, and go on to propose that safety is taught in different contexts, introducing a model which illustrates that process safety education can be imparted through three routes: firstly university education; secondly professional training including internships, on the job training, or continuous professional development; and thirdly through government and regulatory bodies. The authors further break down university education into Bachelor and Master degrees and PhD research. The degree programmes considered by Mkpat et al. (2018) were mainly engineering programmes that incorporated process safety in one or more parts of a wider programme such as chemical engineering. They mention that specific safety engineering degree programmes that address process safety and other areas, such as safety for nuclear or mechanical engineering, exist, although there are not many such programmes. Furthermore, Dee et al. (2015) perform a comprehensive review into how teaching safety has been incorporated in US universities following increased process safety requirements from ABET, concluding that a variety of strategies have been adopted by US universities. From this overview of reviews into teaching safety it is clear to observe that while the importance of teaching process safety is widely recognised, there are a variety of different approaches to safety teaching described in the literature. In recent work by Perrin et al. (2018), three approaches to teaching safety are formally identified as:

i. *incorporating safety as part of all courses within a chemical engineering degree*
ii. *teaching process safety as a separate stand-alone course as part of a chemical engineering degree*
iii. *an integrated approach where process safety is taught in a stand-alone course as well as being integrated into core chemical engineering subjects.*

In this work, the three approaches to teaching process safety formalised by Perrin et al. (2018) are examined within the context of undergraduate chemical engineering degrees.

i. Incorporating safety as part of all courses within a chemical engineering degree

Support for integrating process safety as an inherent part of the chemical engineering degree comes from Benintendi (2016), who includes a number of suggestions on how process safety concepts can be integrated within traditional chemical engineering subjects. A detailed account of how process safety can be integrated into a reaction engineering course is given by Leveneur et al. (2016), although they go on to state that a course on process safety should take place after the integrated course they propose. Perrin & Laurent (2008) also identify links between safety topics and core chemical engineering subjects, although the degree programmes they present also include some form of stand-alone safety courses.

An advantage of incorporating process safety throughout the chemical engineering degree is identified by Perrin et al. (2018) as the ability to coordinate process safety material throughout a degree programme. In addition, they identify that process safety can be an integrating factor within a lecture. However, Perrin et al. (2018) also identify disadvantages associated with this approach, the main one being a potential lack of buy-in to execute this approach amongst teaching staff who may lack the necessary knowledge, interest and experience to support the inclusion of process safety teaching across a degree programme. Furthermore, they suggest there is a lack of a major focus on process safety in this approach. Based on this analysis, Perrin et al. (2018) concluded that the preference in France is to follow an approach where process safety is taught as a separate stand-alone course.

In evaluating this approach we see that there are many advantages of incorporating safety as part of different courses within a chemical engineering degree programme, particularly as it exemplifies to students how safety is relevant to many aspects of their chemical engineering learning and so instils in them a strong safety culture. However, while this approach demonstrates the breadth of safety considerations within chemical engineering there may be a lack of depth in students' safety learning without a focused, high-level, stand-alone process safety course. Furthermore, most authors mentioned here include some form of stand-alone safety teaching. Therefore it is questionable if incorporation of safety in all parts of the degree programme without some form of stand-alone safety teaching is actually performed. However, we acknowledge that there can be significant variation in the format of stand-alone safety teaching, with a particular difference being if the stand-alone element is safety or process safety focused.

ii. teaching process safety as a separate stand-alone course as part of a chemical engineering degree

In the literature, there seems to be overwhelming support and experience of teaching safety as one or two stand-alone courses within a chemical engineering degree programme. Examples include the work of Ferjencik (2007), where the development of an introductory safety engineering course for students on a Bachelor programme complemented an existing safety engineering course which is part of a Masters' programme. Both of these safety engineering courses are delivered to students on programmes including chemical engineering, chemical technology and others. However, Ferjencik (2007) acknowledges that these courses are not the students' first experience of safety education since they have already encountered safety as part of laboratory courses. A similar approach is recommended by Schmidt (2013) who suggests that all process and chemical engineering students in Germany should take a mandatory process and plant safety course whilst studying their Bachelor's degree and then develop these learnings further in a Masters course. However, it is not clear how widely this suggested approach has been adopted. Schmidt (2013) goes on to recommend that further support is also given through exercises and plant visits. Perrin et al. (2018), state that the teaching of safety in France is mainly through stand-alone courses, which are typically spread across different years within the degree programme. While the main focus of safety teaching is in stand-alone process safety courses, there is often support of process safety learning outcomes through laboratory work and, as students progress to Masters level, there is further support of process safety learning in the design project. In other work, Amaya-Gómez et al. (2019) describe in detail the development of four safety-related, open-access modules that were developed as part of an academic-industrial collaboration. The authors describe how these flexible safety modules have been included in undergraduate teaching at 14 Columbian universities in five undergraduate engineering programmes, including chemical engineering programmes where the modules were incorporated in many core chemical engineering courses, in particular process plant design. They go on to discuss how the safety modules have been received favourably as the teaching material provides a basis to customise and allows easy understanding of the topic.

When considering this approach we see that where there is a focus on a stand-alone process safety course or courses, the safety learning outcomes are still supported by other areas of the chemical engineering degree programme, for example through laboratory courses, plant visits or design projects. Therefore it is questionable if stand-alone process safety courses without some form of supported learning in other areas of the chemical engineering programme are carried out in reality.

iii. an integrated approach where process safety is taught in a stand-alone course as well as being integrated into core chemical engineering subjects

In the work of Mannan et al. (1999), their proposal for effective teaching of process safety is for integration of process safety in core chemical engineering topics, supported by a stand-alone course focusing on process safety. They go on to state that a stand-alone course on process safety is in fact a critical aspect of an integrated approach. As already mentioned, Perrin & Laurent (2008) and Perrin et al. (2018) state that safety teaching is generally delivered *via* stand-alone safety teaching courses, although this is generally supported with further safety teaching in some, but not all, aspects of the remaining degree programme. Amyotte (2013) discusses the development of a stand-alone undergraduate process safety course which is delivered to chemical, environmental, biological and materials engineering students. The author then also expands that chemical engineering students receive further education on process safety in reaction engineering and in capstone design courses, as has been indicated by others mentioned in this review (Mannan et al. 1999, Leveneur et al. 2016, Perrin et al. 2018).

Novel methods of integrating process safety teaching within the degree programme have been reported elsewhere. For example, Shallcross (2013a, 2013b, 2014) reports that at the University of Melbourne, safety teaching is introduced to students at an early stage of the programme in a number of different ways. Shallcross (2013a) details how the importance of safety is introduced to all first year engineering students by a study of a past accident, such as the Piper Alpha incident, in an introductory course. This introduction to process safety is further developed in the second year to students on the chemical engineering programme through a further comprehensive study of past incidents (Shallcross, 2013b). In addition to this, two lecture courses that are part of the second year chemical engineering programme start with a 2-4 minute safety share, which mirrors good practice in industry and does not form part of the examinable content of the course. These introductions to safety are not within core chemical engineering subjects such as reaction engineering, but they do convey the importance of safety and also integrate safety into other courses. Furthermore, the introductions go some way to meeting the objective outlined by Mannan et al. (1999) of creating a culture where consideration of process safety is second nature. In other interesting work, Zeng & Zeng (2017) discuss the development of an operation safety education course which uses maintenance scenarios or shutdown-startup tasks to illustrate safety and chemical unit operation learning in the classroom. The scenario selected as the focus of the operation safety education course is a distillation column and its related maintenance tasks. As pointed out by the authors, this approach has the benefit of providing students with an insight into chemical plant operations whilst limiting the burden on industrial companies involved. A brief student perception study is presented by Zeng & Zeng (2017) in which they identified a need for further optimisation of teaching procedures, although deeper analysis and conclusions are not provided. In contrast, Willey et al. (2020) presented their work where an entire course focuses on applying a single hazard evaluation methodology on a particular university research or industrial scenario, utilising research or industrial mentors. Whilst this approach provides excellent depth of learning and insight into real-life scenarios there are potential limitations in the breadth of learning achieved in terms of hazard analysis methods and scenarios studied. For further approaches, examples and contexts on process safety education, see the recent reviews in Dee et al. (2015), Mkpat et al. (2018), Perrin et al. (2018) and Meyer et al. (2019) and references therein.

From this review into the three proposed approaches into process safety teaching it can be concluded that this categorisation of the approaches is not so clear cut. In fact it seems that there is always some form of simultaneous inclusion of safety in other aspects of the chemical engineering degree programme and some form of stand-alone safety course. Therefore it can be concluded that all reported approaches to teaching safety follow a simultaneous integrated approach. The difference can be considered in terms of the extent to which the breadth and depth of safety teaching is considered, where breadth can be viewed as the variety of subjects and processes where safety is incorporated, and depth as the level of detail from foundation to advanced learning and application.

Furthermore, it is important to note there is also ambiguity as to what is considered as safety, what is considered as process safety and where to draw the line between the two definitions. The safety topics mentioned as part of this review and further topics mentioned within the references cited here are wide-ranging. In this work, we use the term process safety to refer to advanced safety topics within areas such as hazard identification, quantification, mitigation and risk management, specifically related to process industries that would typically be found in stand-alone process safety courses. On the other hand we use the term safety to refer to less advanced aspects in these topics, application of these concepts outside of process industries and to topics relevant to a wider range of disciplines such as lab safety or occupational health and safety. However, the term safety is often used as an all-encompassing term to mean both process safety and general safety.

In addition to the different approaches of how to incorporate process safety teaching within the degree programme, it is also important to consider how industrial reality can be brought into the lecture theatre. This largely depends on the specific knowledge and experience of staff within the university departments and also locational context of the university to industry. As proposed by Benintendi (2016), an integrated, systematic and specific relationship with industry is beneficial to process safety teaching. However, there can be difficulty in engaging industry to participate in process safety teaching at university, as cited by Perrin et al. (2018) as often being the case in France.

In 2014, the Institution of Chemical Engineers (IChemE) established the IChemE Safety Centre (ISC), an industry funded, and led, organisation which focuses on improving process safety through knowledge sharing and learning. As part of this goal, the ISC has developed material including detailed case study videos (Kerin, 2016; Kerin and Pollock, 2019); short incident anniversary videos on social media that explain what occurred and where more information can be found; safety related newsletters; and other forms of learning material. Furthermore, the ISC has developed undergraduate learning outcomes to aid process safety education in undergraduate engineering (IChemE, 2018) with input from both industry and academia.

In the USA, the Safety and Chemical Engineering Education (SAChE) programme was established in 1992 as a joint effort between the Center for Chemical Process Safety (CCPS) and the American

Institute of Chemical Engineers (AIChE) (Spicer et al., 2013). The aim of SAChE is to support the teaching of safety in undergraduate and postgraduate programmes of chemical, biochemical and process engineering by providing teaching materials and short courses. In addition, they organise SAChE faculty workshops at chemical plant sites in the US to give teaching staff with limited industrial experience the chance to learn about specific process safety topics and witness their relevance to laboratory, pilot plant or process plant operation. For a comprehensive description of SAChE support mechanisms and material, see Spicer et al. (2013). In addition, AIChE has developed a real-time, interactive teaching tool known as AIChE's web-based Concept Warehouse which contains process safety-related problems that can be used in teaching safety by other instructors globally as detailed by Vaughen (2019). Further useful teaching material on process safety can also been found in resources from the Chemical Safety Board (CSB), most notably amongst these are a series of safety videos (Horowitz & Gilmour, 2007).

To conclude, it is widely accepted that teaching process safety forms an important part of chemical engineering education. There are a range of approaches to incorporating this process safety teaching into a degree programme, from full incorporation in every single course within a programme, to focusing all process safety in one or two stand-alone safety courses. However, these two extremes do not exist in isolation. In reality all approaches to teaching safety from the literature reviewed here ultimately follow an integrated approach where some form of a safety or process safety stand-alone course is supported by integrating safety teaching in other areas of the programme such as laboratory work, design projects, research projects, core chemical engineering subjects and industrial placements.

At this point it is important to note that the publications cited and approaches to teaching safety mentioned in this brief review are all prior to the Covid-19 pandemic. It should be noted that it is likely that the unprecedented circumstances, and potential increase in virtual learning as a result of the pandemic, will place further demands, constraints, but also potential solutions, in how teaching safety is addressed. Furthermore, with a potential increase in virtual operation of chemical plants, the industrial perspective of what is required from safety teaching may change, for instance, with an increased focus on cyber security. As such, approaches to teaching process safety will be a continually evolving and important field.

The aim of this paper is to illustrate how the challenges of teaching safety have been overcome within chemical engineering degree programmes at UCL, where safety teaching has been embedded from a depth and breadth perspective throughout the degree programme. In the next section of this paper, the Integrated Engineering Programme (IEP) teaching framework followed by the UCL Faculty of Engineering Sciences, and how teaching safety has been incorporated within this framework for the chemical engineering degree programme, is presented. Student feedback from a survey carried out at the end of the 2016/17 academic year, where third year students from the first cohort of IEP students and fourth year students in the final cohort of non-IEP students, who were both simultaneously taking a stand-alone Advanced Safety and Loss Prevention course, reflected on their experiences throughout their respective degree programmes. In section 3, the aims and formulation of the student survey are discussed, followed by reflections from analysis of student feedback in section 4. Finally, overall outcomes from the study are concluded.

2. The IEP framework and teaching safety within the IEP chemical engineering degree programme

In 2014/15, UCL Faculty of Engineering Sciences, whose motto is ‘Change the World’, launched its Integrated Engineering Programme (IEP) teaching framework (Sorensen, 2016 and Graham, 2018). The overriding principal of the IEP is that in order to change the world, students need to be taught differently, and this is achieved through a scenario- and problem-based engineering curriculum.

Fundamental engineering knowledge is taught at the same time as giving students the opportunity to apply and extend their fundamental knowledge on research-based projects. In addition, students have the opportunity to learn and develop their professional skills. Projects carried out as part of the IEP teaching framework tackle discipline-specific technical problems, such as an examination of separation processes for the petrochemical industry or for anthropologists in the Amazon area of Brazil, or real world challenges such as energy and health in various global locations. The projects and scenarios are carried out in both interdisciplinary and discipline-specific teams. The ultimate aim of the IEP is to produce well-rounded engineers with a strong understanding of fundamental engineering principles, and an appreciation of the complexity and context of engineering problems, in strong alignment with the learning outcomes of accreditation bodies and the needs of industry.

Within the IEP teaching framework, UCL Engineering Sciences offer a Bachelor (BEng) and Integrated Masters (MEng) in Chemical Engineering, with options to spend the penultimate year on industrial placement, or to specialise in biochemical engineering, chemistry or engineering mathematics in the final year, or to spend the final year abroad. Irrespective of which of these options is taken, the first 3 years of the two programmes are the same since most courses in the first 3 years are compulsory, as is common with other degree programmes in the UK. This enables proper planning, introduction and delivery of key concepts, such as safety, from the start of year 1 until graduation after 3 or 4 years. An overview of the IEP chemical engineering programme in terms of courses taken, their alignment to IEP Faculty-wide content, core chemical engineering content, design, experimentation, research and elective content across the 4 years of the degree programme is shown in Fig. 1. In terms of student and staff numbers on such a degree programme, the current undergraduate cohort at UCL Chemical Engineering is typically 110-140 students per year, taught by 26 academic staff and 10 lecturers (teaching). The focus of this study is to consider specifically how the teaching of safety has been incorporated into the IEP chemical engineering degree programme and how this compares to the approach in the previous non-IEP chemical engineering degree programme. It should not be considered an evaluation of the faculty-wide IEP framework as this has been considered elsewhere (Graham, 2018).

Insert Fig. 1.

Fig. 1. An overview of the chemical engineering programme at UCL Engineering Sciences.

In terms of safety teaching within the IEP chemical engineering programmes, a systems approach has been taken which inherently embeds safety learning throughout the degree programme from the first week in Year 1 to graduation at the end of Year 3 or 4 (Pollock & Sorensen, 2018). Fig. 2 shows how safety is introduced and developed from a depth and breadth perspective across the entire chemical engineering degree programme. Here, most courses are 7.5 ECTS, whilst the capstone design project in Year 3 and the research project in Year 4 are both 15 ECTS.

Insert Fig. 2.

Fig. 2. An overview of how safety has been inherently embedded into the chemical engineering programme at UCL Engineering Sciences from depth and breadth perspectives.

The depth of the programme reflects how safety is immediately introduced in Year 1 through the Design & Professional Skills I course where concepts of safety are introduced straightaway and applied to society in general and to situations to which 18 year olds can relate, for example a risk assessment of cycling through London. This is extended throughout Year 1 and in the safety topic of the Design & Professional Skills II course in Year 2 to have more of a focus on process industries through the examination of past accidents, risk reduction strategies and hazard evaluation methods. Another important safety topic that is introduced in Year 2 are hazards and control of exothermic reactions. Introduction of this topic at this point in the curriculum fulfils recommendations from the

Chemical Safety Board (CSB) that awareness of reactive hazards should be incorporated into the curriculum following the T2 Laboratories accident (Crowl & Louvar, 2011). To overcome the challenges of teaching safety in a classroom environment and students' lack of industrial experience, the realities of real-life industrial problems, decision making constraints and consequences are introduced through safety videos from the IChemE Safety Centre (ISC) (Kerin, 2016; Kerin and Pollock, 2019) and Chemical Safety Board (CSB) (Horowitz and Gilmour, 2007). Furthermore, as is common in industrial safety meetings and as suggested by Shallcross (2014), introductory safety lectures are started with a brief safety moment often relating to the safety topics to be covered in the lecture. The depth of safety learning is further built upon in Year 3, where students apply their safety learnings to their capstone design project (15 ECTS), which is a more complex and detailed industrial process problem than previously considered in their first two years of study. Concurrently in Year 3, students take a compulsory Advanced Safety and Loss Prevention course (7.5 ECTS) to further develop their in-depth safety learning, focusing on hazard identification, risk management and quantitative risk assessment.

The breadth of safety learnings, and how these can be applied across different industries and at different stages within the design cycle are also key learning outcomes of the IEP framework. In Years 1 & 2, students perform 6 week-long mini design projects called Scenarios (see Figure 1). Each Scenario has a different engineering challenge or industry as its focus, for example, biofuels, petrochemicals, pharmaceuticals or air separation. In each of these Scenarios, there is a safety element and students work on a different safety deliverable, such as the development of a risk matrix for an LNG facility or the development of a safety newsletter for the air separation industry. In the capstone Year 3 design project, the breadth of hazard evaluations that can be applied throughout the process design cycle are examined in detail. These include investigation of past accidents and material safety data sheets (MSDS) relevant to the process under development during conceptual design in preparation for performing a group Preliminary Hazard Analysis. As the design moves into the preliminary design stage, students perform a HAZOP within their groups on the process they are developing, brainstorming ideas and capturing discussions. Finally, in the detailed design stage students individually perform a safety study such as a Safety Integrity Level (SIL) Analysis on the process unit that they are individually designing; considering the hazardous events relevant to their process unit, and quantifying the reliability of their system using a Fault Tree Analysis. Such an approach to safety studies within the capstone design project gives students an appreciation of the information available at different stages within the project and the corresponding hazard evaluation techniques that can be employed, as discussed by Towler & Sinnott (2012). For a further detailed description of the depth and breadth approach taken to teaching safety within the IEP framework see Pollock & Sorensen (2018).

A further benefit of embedding safety throughout the curriculum means that safety is a topic that is continually discussed and debated by students who may come from culturally diverse backgrounds (50% of the cohort are overseas students). Perceptions of what constitutes 'safe' may vary across the cohort, but as time progresses students can develop their understanding based on a wide range of applications and contexts to become well-rounded, safety-aware and responsible chemical engineers regardless of their background and understanding on entry to the programme. This again aids in fulfilling the objective of Mannan et al. (1999) of creating a culture in which process safety is second nature.

Referring back to the review of approaches to teaching safety in section 1, it is clear that the approach to teaching safety within the IEP chemical engineering degree programme follows an integrated approach with significant emphasis on both the breadth and depth of safety teaching and learning. In comparison, in the previous non-IEP chemical engineering degree programme, teaching safety again followed an integrated approach, however, the breadth and depth of this safety teaching was not so developed. In the non-IEP chemical engineering programme, safety teaching was focused in a variety of safety tasks completed within the capstone third year design project covering safety studies that would be completed at different stages of the process design cycle. This was further supported by an optional, fourth year stand-alone process safety course for the MEng programme. Increased depth of safety teaching within the IEP chemical engineering programme is achieved by introducing safety teaching in the first year; addition of an introductory stand-alone safety topic as part of the second year Design and Professional Skills II course; and concluding with a compulsory process safety stand-alone course and capstone design project safety tasks in the third year. The breadth of teaching safety has been widened by increasing the number and variety of safety tasks performed, and the number of process industries studied particularly within the mini-design project Scenarios completed in the first two years. For the MEng programme, further safety aspects are included in the research project.

The overall success of UCL's IEP chemical engineering degree programme has been demonstrated through a number of metrics. Firstly, through the successful accreditation of the IEP chemical engineering degree programmes by the IChemE in 2016. In feedback from the IChemE, the department's vision to produce graduates with a strong safety ethos was particularly recognised. Furthermore, in a report released by MIT School of Engineering (Graham, 2018), UCL Engineering was identified as one of four global emerging leaders in engineering education. The IEP's approach, which focuses on application of knowledge into practice on authentic engineering problems which allows students to reinforce their learning, was particularly commended. Moreover, UCL Engineering and its innovative IEP teaching framework was further recognised by winning the Collaborative

Award for Teaching Excellence (CATE) in 2017 which is awarded and funded by the UK's Higher Education Academy (Advance HE, 2020).

3. Aims and formulation of student survey

In the academic year 2016-17 there was a unique occurrence where third year students from the first cohort on the IEP framework, and fourth year students in the last cohort of the non-IEP framework, were both taking the same, stand-alone process safety course on Advanced Safety and Loss Prevention (7.5 ECTS). This situation arose since as part of the re-design of the chemical engineering degree programme in response to the introduction of the IEP teaching framework the elective stand-alone process safety course in the fourth year of the non-IEP programme was moved to the third year, to run alongside the capstone design project, and was changed to a compulsory course.

As such, both third year IEP and fourth year non-IEP student cohorts took the same stand-alone process safety course in 2016-17, each with a different prior learning experience which gave the unique opportunity to survey student perceptions, awareness and understanding of safety and how teaching safety had been delivered throughout the IEP and non-IEP chemical engineering degree programmes. This differs from previously discussed literature studies which typically focus on the development of a new safety course (Ferjencik, 2007, Amyotte, 2013), perceptions in the inaugural year of a course (Amaya-Gómez et al., 2019) or provide an overview of how safety is taught in different institutions but typically without providing a student perspective (Perrin et al., 2018).

In the third term of the academic year in 2016-17, a voluntary online survey was released after all coursework marks had been returned and after the exam had been sat by students, but before the exam results were released. This timing was chosen so that perceptions were still fresh in the minds of students whilst as the same time ensuring responses would not be influenced by knowledge of marks obtained in the final exam. An online survey was chosen to maximise anonymous student engagement during a busy exam period. Focus group interviews were not possible as many students had already returned home. A total of 20 survey questions were formulated with the aim to collect data on the following themes:

i. *Factual data giving an indication of programme (BEng or MEng – IEP or MEng – non-IEP) and gender of responding students;*
ii. *Perceptions on awareness and understanding of safety;*
iii. *Perceptions of when and where safety concepts were introduced and applied during the degree programme;*
iv. *Perceptions of preparedness for the capstone design project;*
v. *Evaluation of effectiveness of different methods for teaching safety and embedding safety within the degree programme.*

Responses to questions were typically formulated as a tick box. In responses where agreement to the statements in the question had to be shown, a scale of '*Strongly disagree', 'Somewhat disagree', 'Neither agree nor disagree', 'Somewhat agree'* and *'Strongly agree'* was used. In the introductory preamble of the online survey the aims of the survey, in terms of an evaluation of how inherent integration of safety in their degree programme had been received, and the impact it had on their understanding of safety and further development of safety teaching methods, were made clear. Furthermore, it was stated that the survey was not an evaluation of the stand-alone process safety course but rather an evaluation of how safety had been taught throughout their entire degree programme.

Before the student perceptions themselves are examined, it is important to compare and contrast the two cohorts of students that took part in the survey, see Table 1. From this comparison it can be seen that third year IEP students had prior experience of Scenarios and Design and Professional Skills lecture courses. On the other hand, fourth year non-IEP students had prior experience of the capstone third year design project while the IEP students were taking the capstone third year design project at the same time as the stand-alone process safety course. Both IEP and non-IEP cohorts had experience of in-class examples, assessed and unassessed, although where they had encountered these examples, and the type of examples, differed based on their experiences as outlined above.

Table 1 Comparison of experiences of students on IEP and non-IEP chemical engineering degree programmes that took part in the teaching safety survey in the third term of 2016-17.

Insert Table 1.

4. Reflections on student feedback

In this section the results from the student survey will be analysed and discussed. The structure of this section follows the 5 themes within the survey, as outlined in points i to v in the previous section. For each of the 5 themes within the survey the results will be presented and immediately discussed to enable reflection of the survey results and their implications. This section then concludes with an overall reflection section which brings together points from the different themes of the survey, summarising their overall implications and reflecting how this fits within the context of the different approaches to teaching safety as reviewed in section 1. The paper then concludes with overall conclusions in the next, and final, section.

i. Factual data giving an indication of programme and gender of responding students

The online survey was sent to 176 students enrolled on the stand-alone process safety course in 2016-17; 44 responses were received, equating to a 25% student engagement with the online survey. In order to differentiate if responses were from IEP or non-IEP students, the first question in the survey asked the year of study with potential responses either year 3 or 4. There were 35 and 9 respondees who indicated they were in their third and fourth year respectively, corresponding to a 28% and 17% response rate amongst third and fourth year students respectively. Reasons for a lower response rate amongst the non-IEP students may have been that they felt the survey was more aimed at IEP students who had taken part in Scenarios and other IEP elements that had not been available to the non-IEP students. Furthermore, all non-IEP students were graduating Masters' students, whilst amongst the responding IEP students in the third year 69% of them were returning the following year to complete their Integrated Masters. The difference in response rates between IEP and non-IEP students means that while significant conclusions can be drawn from the responses of IEP students, and will be the focus of this paper, the responses of non-IEP students can only be used to compare and contrast with the opinions of the IEP students. It should also be noted that there is a slight gender bias in the responses of the IEP students, where only 20% of IEP respondents are female compared to 26% in the IEP cohort overall.

In terms of accuracy of survey responses and resulting conclusions, it was assumed that all students who indicated they were in their third year followed the IEP chemical engineering degree programme. However, there could have been variations, for instance due to i nterruption of studies some students in the third year may not have been following an IEP chemical engineering degree programme. Studying all survey responses it was estimated that this may have been the case for up to 3 of the third year responders. Upon reflection a better formulation would have been to explicitly ask on which degree programme students were registered. Furthermore, it was noted that some student responses for some questions were omitted and/or not possible, for example a third year student responding to a question on the fourth year design project or a fourth year student responding to a question on IEP Scenarios. While there could be small inaccuracies for these reasons, there may be inaccuracies for other reasons such as responders not reading or misreading a question. As such it was decided to evaluate all responses for a given question and accept overall trends whilst acknowledging potential minor inaccuracies. In a few instances infeasible responses were excluded from the analysis, if this is the case then it is explicitly mentioned. In the following sections, results are presented in terms of percentage of the IEP (third year) and non-IEP (fourth year) students who indicated a given response for a particular question where the total number of IEP or non-IEP responders is typically 35 and 9, and is no lower than 31 and 7, respectively. Due to the small data set obtained for this single snapshot in time it was not possible to perform a rigorous quantitative analysis, instead this study should be viewed as an indication of student perceptions.

ii. Perceptions on awareness and understanding of safety

A key learning outcome of the IEP teaching framework is a broad understanding of the complexity and context of engineering problems (Sorensen, 2016, Graham, 2018). Safety is strongly linked to this since at every stage in the career of a chemical engineer, and in every stage of a process engineering project, there is significant consideration of the associated hazards, risks and consequences by the chemical engineer and how these can be mitigated. To determine how effectively this awareness and understanding of safety has been conveyed to students during their undergraduate studies, students were asked to indicate agreement to different statements on their perceptions of their awareness and understanding of safety. Responses to these questions are shown in Table 2.

Table 2 The percentage of students who indicated *'Strongly agree'* or *'Somewhat agree'* with statements asking about their perceptions of their awareness and understanding of safety.

Insert Table 2

From the results presented in Table 2 it is important to note that both cohorts of students feel they have a good understanding of the importance of safety in chemical engineering, in society in general and of inherently safe design. These key learning outcomes are very well conveyed to students irrespective of their degree programme, although 2-5% stronger agreement is observed amongst IEP students. In terms of awareness of safety, best practices, technical knowledge and an appreciation of safety culture being effectively imparted, agreement in both cohorts goes down. However, there is still strong agreement, particularly amongst IEP students who note 74% agreement, although this gives an indication of an area for further improvement within the teaching safety curriculum.

iii. Perceptions of when and where safety concepts were introduced and applied during the degree programme

Now that students have validated *their* perception as having a good understanding of the concepts of safety, the survey moved on to examine when in the degree programme these concepts were introduced and when students had the opportunity to apply safety concepts. The results from these questions are shown in Fig. 3 and Fig. 4.

Insert Fig. 3.

Fig. 3. Student responses when asked in which year of the programme were you first introduced to the concepts of understanding risk, hazards and accidents. Responses from IEP students are shown in grey shading and responses from non-IEP students are shown with a square grid pattern.

Insert Fig. 4.

Fig. 4. Percentage of student responses who indicated *'Strongly agree'* or *'Somewhat agree'* when asked if they had the opportunity to apply their safety knowledge during the degree programme in

coursework or lectures in Year 1, 2, 3 and 4. Responses from IEP students are shown in grey shading and responses from non-IEP students are shown with a square grid pattern.

From Fig. 3 it can be observed that 57% of IEP students felt that they were first introduced to the concepts of understanding risk, hazards and accidents in their first year of study compared to only 22% of non-IEP students. This compares further to an overall perception from non-IEP students that they were first introduced to these same concepts mainly in their second year of study (most likely as part of their laboratory course). Furthermore, from Fig. 4, it can be observed that 52% of IEP students felt that they were given the opportunity to apply their safety knowledge in coursework or lectures immediately in the first year compared to only 29% of non-IEP students. Moreover, as both cohorts of students progress through the years of their study, both cohorts felt they were given more and more opportunity to apply the safety knowledge they were gaining. This culminates in a spike of at, or nearly at, 100% in the third year, which equates amongst the IEP students to their experiences in the capstone design project *and* the stand-alone process safety course, while for non-IEP students this spike can be attributed solely to the capstone design project since the stand-alone process safety course was taken in the fourth year. Fig. 3 and 4 show the success of the IEP chemical engineering degree programme in terms of achieving its key aims of producing engineers with a broad understanding of the context of engineering problems by providing ample opportunities to apply their fundamental knowledge on industry-orientated, real-life engineering projects right from the start of their degree programme.

iv. *Perceptions of preparedness for capstone design project*

After establishing that students within the IEP framework perceived themselves to have a good understanding of safety after introduction and application of the concepts of safety in the early years of their degree programme, the survey moved on to consider more complex application of safety concepts and understanding. Specifically, students were asked, '*based on the first two years* *of the programme, and the courses running concurrently in the third year, did they feel prepared to tackle the safety aspects of the third year design project?'* A comparison of responses from IEP and non-IEP students is shown in Fig. 5. From Fig. 5 it is clear to see opposing views from the different cohorts of students. Amongst the IEP students the modal response is agreement with this statement, shared amongst 71% of the IEP students, while only 22% agreement is observed amongst non-IEP students. In fact, amongst the non-IEP students the modal response is disagreement with the statement regarding preparedness for safety aspects of the capstone design project at 44%. From this is can be concluded that the IEP approach of inherently embedding safety throughout the IEP chemical engineering degree programme has been felt by students and indeed provides them with the advantage of feeling prepared for safety aspects within the capstone design project.

Insert Fig. 5

Fig. 5. A comparison of responses when students were asked about preparedness for the capstone third year design project. Responses from IEP students are shown in grey shading and responses from non-IEP students are shown with a square grid pattern.

v. Evaluation of effectiveness of different methods for teaching safety and embedding safety within the degree programme

To evaluate different approaches to teaching safety, a series of further survey questions focused on the different teaching methods utilised within the IEP chemical engineering degree programme. Fig. 6 illustrates students' responses when asked how effective different learning methods have been when learning about safety. From Fig. 6 it is rewarding to observe that the introduction of Scenarios as a teaching method, a key element of the new, innovative, real-life and industrially focused IEP teaching framework, has been perceived as effective with 81% of respondents indicating that they found the Scenarios to be '*Somewhat effective*' or '*Very effective*'. It should be noted that IEP responses to evaluate the effectiveness of Scenarios was evaluated out of 32 students, as three of the Y3 students had indicated they had not taken part in Scenarios in this question, for all other teaching methods IEP responses were evaluated out of 35 students as per other questions.

This compares to responses from non-IEP students where in-class exercises, either assessed or unassessed, were previously the most effective teaching method for safety. Also important to note are the responses regarding technical lectures, such as the stand-alone process safety lecture course and safety lectures within the capstone design project. While only 50% of non-IEP students found this an effective method, this grew to 77% amongst IEP students and was the most successful teaching method after Scenarios, more so than in-class exercises. There could be a number of reasons for this. For example, by having the opportunity to apply safety knowledge as part of the IEP chemical engineering degree programme in Scenarios, students may have gained more powerful insights when material was formally taught within a lecture setting. Furthermore, by bringing the stand-alone course on process safety forward from the fourth year to the third year, and making it compulsory, may have increased its effectiveness. This was achieved firstly by running the stand-alone process safety course concurrently alongside the capstone design project, learnings between the two courses can be shared and enhanced, and secondly, by developing continuation of depth in safety learning by placing the stand-alone process safety course directly after initial safety learnings contextualised within society in general and the process industries that are covered as part of the 'Design and Professional Skills' lecture series in Year 1 and 2.

Insert Fig. 6

Fig. 6 '*Somewhat effective*' and '*Very effective*' responses from students when asked 'How effective do you feel the following learning methods have been when learning about safety?' Responses from IEP students are shown in grey shading and responses from non-IEP students are shown with a square grid pattern.

Extending this evaluation of effectiveness of teaching methods, students were asked their perceptions in terms of '*What aspect of the programme has effectively imparted an awareness of safety to prepare you for an industrial role?'* The responses shown in Fig. 7 from the IEP students show the success of the depth and breadth approach to teaching safety that has been developed as part of the IEP teaching framework. As shown in Fig. 7, IEP students perceived the capstone design project and stand-alone process safety course as the most effective methods, scoring 89% and 82%, respectively. This was closely followed by Scenarios which were rated as effective by 77% of respondents (although effectiveness of Scenarios was rated by 31 students since 3 had indicated they had not done Scenarios and a fourth had not answered). Finally, 48% of respondents also indicated that other lectures, unspecified but could include lectures as part of 'Design and Professional Skills' or other core engineering content such as 'Separation Processes' or 'Reaction Engineering' were also effective in imparting an awareness of safety for an industrial role. It should be noted that 'Advanced Design' is a separate M-level course (Process Systems Engineering and Design) taken in the fourth year and so a response was only applicable from the non-IEP students who were in their fourth year. Furthermore, it can be seen that whilst the stand-alone process safety course and the capstone design project are evaluated to be most effective for imparting awareness of safety for an industrial role amongst non-IEP students, the IEP students perceived these methods to be even more effective. From this it can be inferred that the depth of safety teaching within the IEP chemical engineering degree programme, with the introduction of Scenarios and project-based learning early on in the curriculum, enhances the success of teaching methods encountered at later stages of the degree programme.

Insert Fig. 7

Fig. 7 '*Somewhat effective'* and '*Very effective'* responses from students when asked 'What aspect of the programme has effectively imparted an awareness of safety to prepare you for an industrial role?' Responses from IEP students are shown in grey shading and responses from non-IEP students are shown with a square grid pattern.

Finally, students were asked *'For all accredited programmes, aspects of risk and safety should be embedded throughout the programme, i.e. mentioned or considered in most courses. Do you feel this has been the case for your programme?'* In their response to this statement, IEP students indicated 71% agreement compared to 67% by non-IEP students. From this it can be concluded that while the majority of respondents from both cohorts perceived safety to be embedded across their programme, the response was slightly higher amongst IEP students. However, in light of responses by IEP students to questions regarding the effectiveness of teaching methods (Fig. 6 & 7), which show a spread of responses to different methods throughout the IEP teaching framework, further signposting of where safety is embedded in the IEP teaching framework should be indicated to students.

vi. Overall reflection of student perceptions

As with most other student surveys, students were given the opportunity to voice their opinions in open-ended questions asking them to comment on aspects of the programme where safety could be covered more, and any other comments related to their experience of learning safety within their programme. From the comments returned by the students it was very rewarding to observe that the goals of inherently embedding safety teaching throughout the IEP chemical engineering degree programme had been identified by the students, with one student commenting *"I think that courses are taught with a safety aspect in mind so that safety becomes part of our everyday critical thinking",* while another stated *"…overall the department has done a good job of gradually increasing the importance of safety for the students throughout the academic years".* Additional ideas on how to further embed safety into the curriculum were also interesting, such as one student suggesting *"I think it would have been good to have a Scenario that focused on safety",* presumably entirely focused on safety as all Scenarios contain an element of safety. These student comments show that the challenge, as quoted from Mannan et al. (1999) near the start of section 1, of creating a culture in which the consideration of process safety issues is second nature has been achieved.

To further evaluate the success of the approaches to teaching safety within the IEP chemical engineering degree programme, and to validate the conclusions on student perceptions drawn from the student survey, marks from the stand-alone process safety course assessments were analysed. The average mark for coursework in the stand-alone process safety course for both the IEP and non-IEP cohort of students was the same and was a high first class degree mark. The overall average mark of the stand-alone process safety course for both the IEP and non-IEP cohorts was again a high first class degree mark, although the average mark for the non-IEP cohort was 2.2% higher than for the non-IEP cohort. This could be because the significantly smaller number of students on the non-IEP chemical engineering programme were all graduating MEng students and not a mixture of penultimate-year MEng and graduating BEng students as in the IEP cohort, but it could also be because the non-IEP students were generally a year older and had an additional year of study under their belt. Further validation of the conclusions from this study through the analysis of third year design project safety assessments is not comparable since the format of the design project safety assessments and the teaching staff involved in assessment between the two cohorts changed with the introduction of the IEP.

Overall it can be concluded that the increased depth and breadth of teaching safety within the IEP chemical engineering degree programme has been perceived by IEP students. In particular, the new teaching framework has led to an increased perception of preparedness for the capstone design project and an increased perception of the effectiveness of teaching methods for preparation for an industrial role. Whilst overall it can be concluded that there is a similarity in student perception of understanding safety irrespective of degree programme, it can be seen that there is a higher perception of awareness of safety within the IEP cohort. From student comments, this increased awareness of safety together with an increased depth and breadth of safety teaching has been perceived by students, and has led to an indication that consideration of process safety is starting to become second nature.

5. Conclusions

The teaching of safety is of fundamental importance within a chemical engineering degree programme. There are a variety of methods for teaching this important topic from incorporating safety into every course within a degree programme; to focusing all learning in one or two stand-alone process safety courses, and finally a simultaneous integrated approach in which a stand-alone course is supported by incorporation of safety teaching in some, if not all, other aspects of the programme. From the literature review it was concluded that in reality all approaches follow an integrated approach with varying amount of, and focus on, stand-alone safety courses and incorporation throughout the chemical engineering degree programme. Identifying the extent of integration is often dependent on the strengths in terms of knowledge and experience of teaching staff and locational context of the university.

Within the recently established Integrated Engineering Programme (IEP) teaching framework at UCL, the depth and breadth of teaching safety within the IEP chemical engineering degree programme has been increased, with safety teaching inherently embedded throughout. Firstly, from a depth perspective, where safety is introduced immediately in the first year and runs throughout all years of the degree programme. Secondly, from a breadth perspective, in terms of the range of instances within the process design cycle, and examples from different industries, where safety is embedded. Furthermore, innovative project-based teaching methods are employed, such as mini design projects, known within the IEP framework as Scenarios, as well as incorporation of safety into laboratory experimentation, in-class examples, design projects and lectures. In addition, safety videos, such as those produced by the IChemE Safety Centre (ISC) and Chemical Safety Board (CSB) are used to exemplify real-life industrial incidents. Through these wide-ranging approaches the challenges of safety teaching within the confinements of the classroom, where students have limited industrial experience and where they are still developing their core chemical engineering knowledge, are addressed with the aim of creating well-rounded and safety-aware graduates with a strong safety culture.

The success of this novel new approach has been corroborated from student feedback, where over 90% of students feel they have a good understanding of the importance of safety within chemical engineering, society in general and the concept of inherently safer design. Furthermore, students recognise that safety is introduced immediately in the first year and feel they have continually growing opportunities to apply their safety learnings as they proceed through their studies, leading them to feel prepared to tackle safety in their capstone design project and future industrial roles. The success of this approach has been further recognised through the successful accreditation of the IEP chemical engineering degree by the IChemE in 2016 in which the department's vision to produce graduates with a strong safety ethos was particularly recognised. Finally, to conclude, the success of such a comprehensive safety teaching programme could not be achieved without the efforts of all teaching staff involved in every aspect of safety teaching, with strong academic, industrial and laboratory experience.

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Figures

Fig. 1

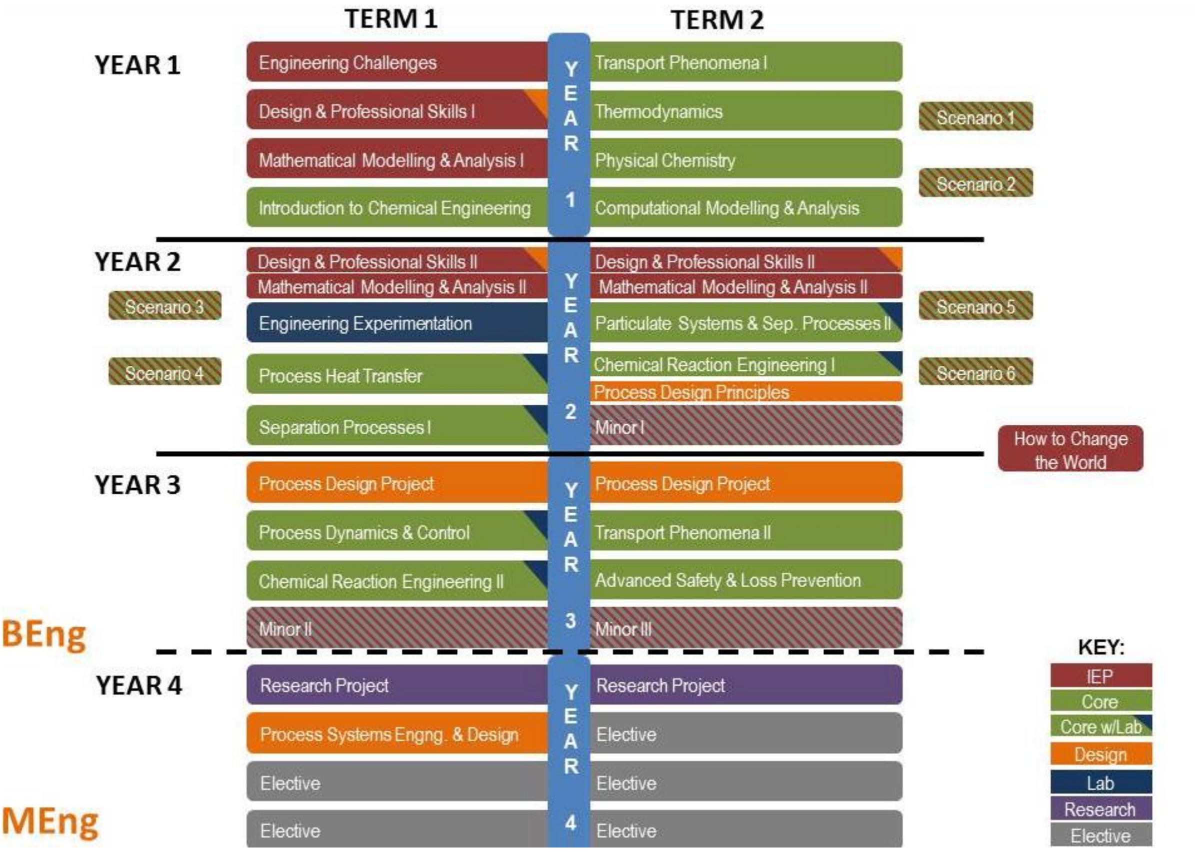


Fig. 2

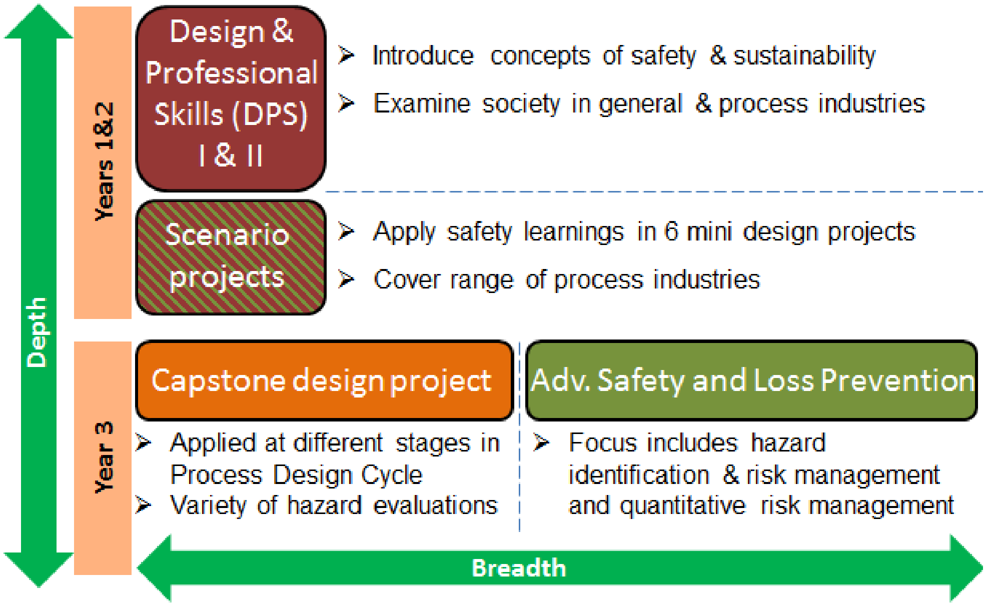

Design & Professional Skills (DPS) I & II
Introduce concepts of safety & sustainability
Examine society in general & process industries
Scenario projects
Apply safety learnings in 6 mini design projects
Cover range of process industries
Years 1&2
Capstone design project
Applied at different stages in Process Design Cycle
Variety of hazard evaluations
Adv. Safety and Loss Prevention
Focus includes hazard identification & risk management and quantitative risk management
Year 3
Depth
Breadth

Fig.3

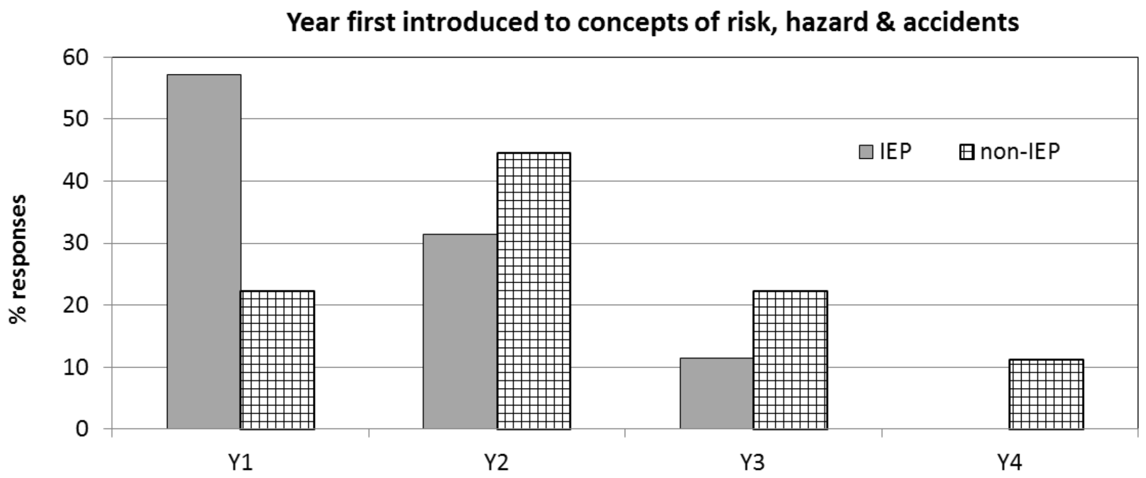

Year first introduced to concepts of risk, hazard & accidents
% responses
0
10
20
30
40
50
60
Y1
Y2
Y3
Y4
IEP
non-IEP

Fig. 4

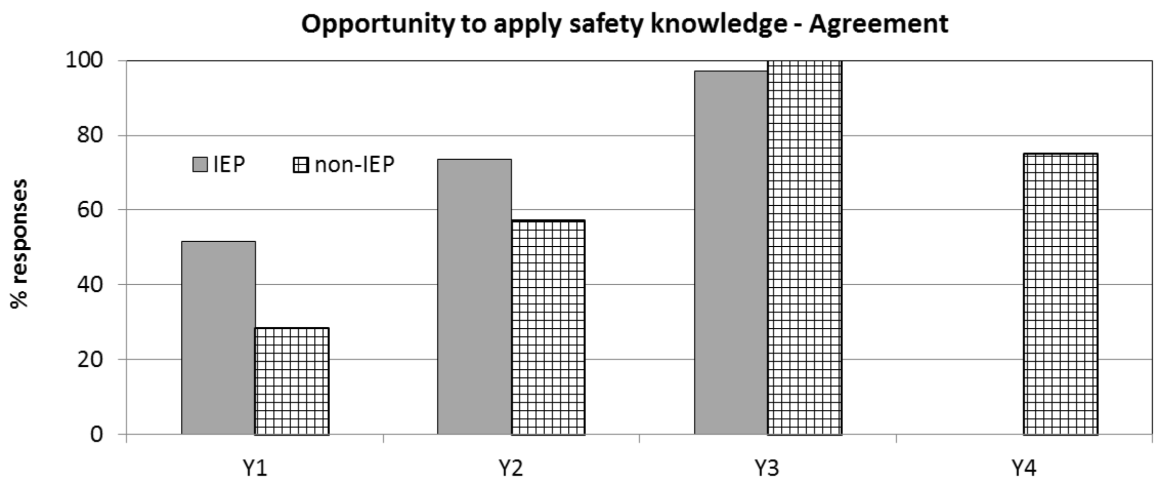

Opportunity to apply safety knowledge - Agreement
100
80
60
40
20
0
% responses
IEP
non-IEP
Y1
Y2
Y3
Y4

Fig. 5

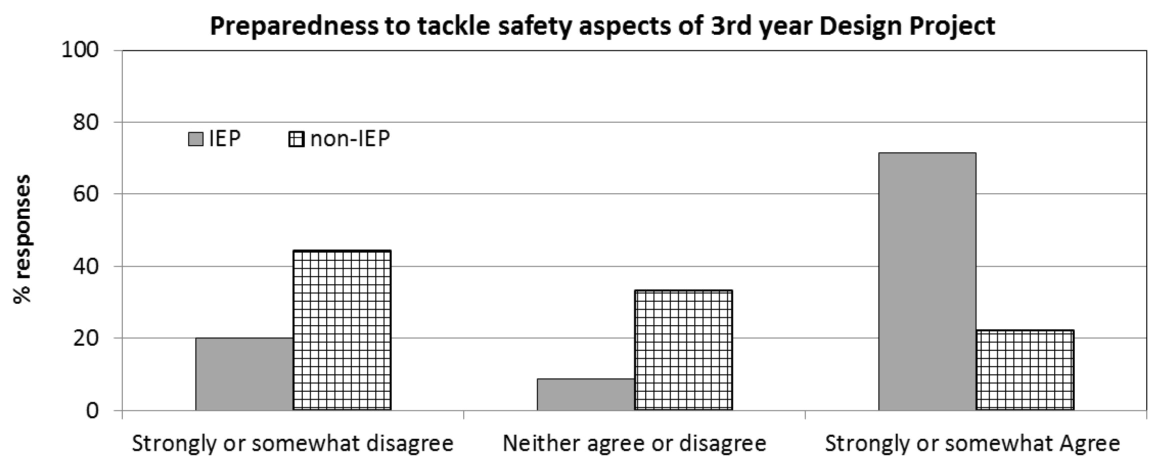

Preparedness to tackle safety aspects of 3rd year Design Project
100
80
60
40
20
0
% responses
IEP
non-IEP
Strongly or somewhat disagree
Neither agree or disagree
Strongly or somewhat Agree

Fig. 6

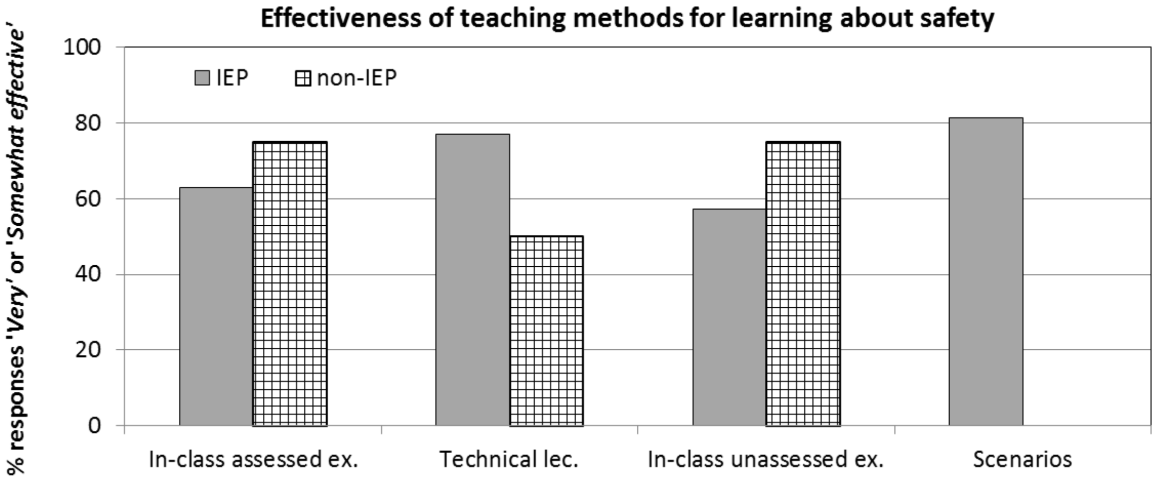
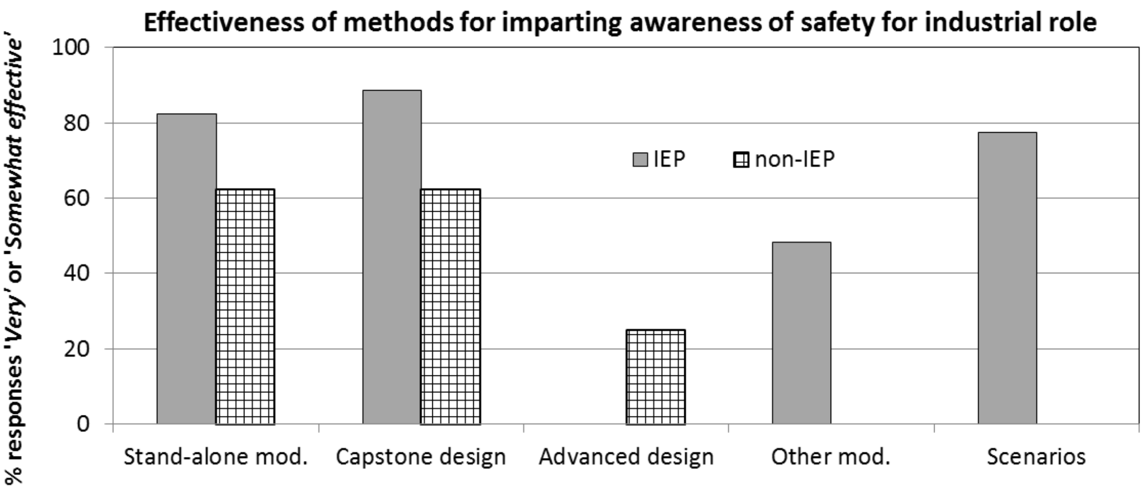

Effectiveness of teaching methods for learning about safety
% responses 'Very' or 'Somewhat effective'
100
80
60
40
20
0
IEP
non-IEP
In-class assessed ex.
Technical lec.
In-class unassessed ex.
Scenarios

Fig. 7


Effectiveness of methods for imparting awareness of safety for industrial role
% responses 'Very' or 'Somewhat effective'
100
80
60
40
20
0
IEP
non-IEP
Stand-alone mod.
Capstone design
Advanced design
Other mod.
Scenarios

Tables

Table 1

Programme	**IEP**	**Non-IEP**
Year of study in 2016-17	Third	Fourth
Student experience *before* 2016-17	– Scenario-based project learning – IEP courses such as Design & Professional Skills I & II – In-class examples – assessed and unassessed	– In-class examples – assessed and unassessed – Capstone 3rd year design project
Student experience *during* 2016-17	– Capstone 3rd year design project – Stand-alone process safety course	– Stand-alone process safety course

Table 2

Question: Do you feel …	**% IEP responses**	**% non-IEP responses**
that an awareness of safety, best practices, technical knowledge & an appreciation of safety culture has been effectively imparted?	74	67
you have a good understanding of the importance of safety in chemical engineering?	91	89
you have a good understanding of the importance of safety in society in general?	94	89
you have an understanding of what inherently safe design means in the chemical industry?	91	89