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Complexity and Uncertainty Management in Process Safety Education

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At the end of the past century, the field of process safety was initiated thanks to the skills and industrial experience of pioneers such as Trevor Kletz, Hans Pasman, Joaquim Casal and André Laurent. Pioneers relied on their skills and desire to solve problems since formal safety education was not developed until the late 1990s with examples such as the Mary Kay O'Connor Process Safety Center at the Texas A&M University in the US. After 30 years of Kletz's first safety-related book, the panorama has changed with engineering education integrating safety, thanks to initiatives such as ABET accreditation and others detailed in recently published reviews. However, safety is still a concept being debated and constructed in both education and practice, with open questions such as "How is safety linked to risk?" The authors view process safety as a set of evolving tools and growing knowledge supporting risk assessment and aiding decision-making. This process is carried out under uncertainty related to the complexity of the systems, the availability of data and the competence of the analysts involved. Uncertainty and its management constitute critical challenges for process safety educators and practitioners. In this context, the authors want to answer: how does process safety education integrate complexity and uncertainty management? To answer it, the authors conduct a review of formal educational programs and specific courses with a focus on uncertainty, as well as their teaching and consulting experience. The results help to formulate a set of recommendations to improve the handling of complexity and uncertainty management in different levels of safety education.

1. Introduction

Growing complexity and economical optimization constraints make the development of new hazardous facilities a challenge for all engineering fields involved. At the same time, the deployment of new chemical and petrochemical facilities continues to increase (Reniers, Amyotte 2012). The complexity and economic constraints of these facilities can lead to failures and possibly to major accidents with unacceptable consequences such as off-site casualties and environmental damage. Process safety engineers are in charge of the risk management processes that prevents, controls and mitigates such events and their consequences. Such responsibility requires competence from all engineers involved and particularly from the process safety engineers, which is built through learning at all educational levels: undergraduate and postgraduate education and continuous professional development. Mkpat et al. (Mkpat, Reniers, Cozzani, 2018) present a detailed review of process safety education, with a particular emphasis on the way chemical engineering curricula integrate process safety and the interactions between key stakeholders, i.e., academia, industry, government. At the University education level, both Mkpat et al. (Mkpat, Reniers, Cozzani, 2018) and Dee et al. (Dee, Cox, Ogle, 2015) identify those main topics being taught include mechanical integrity, hazards identification, consequence, and emergency planning. These topics can be associated with the steps of the risk management process as described by ISO 31000:2018, with an essential focus on the components of risk assessment. Figure 1 presents the elements of risk management, and identifies those predominantly addressed by practitioners in the industry and therefore with less learning components in academia.

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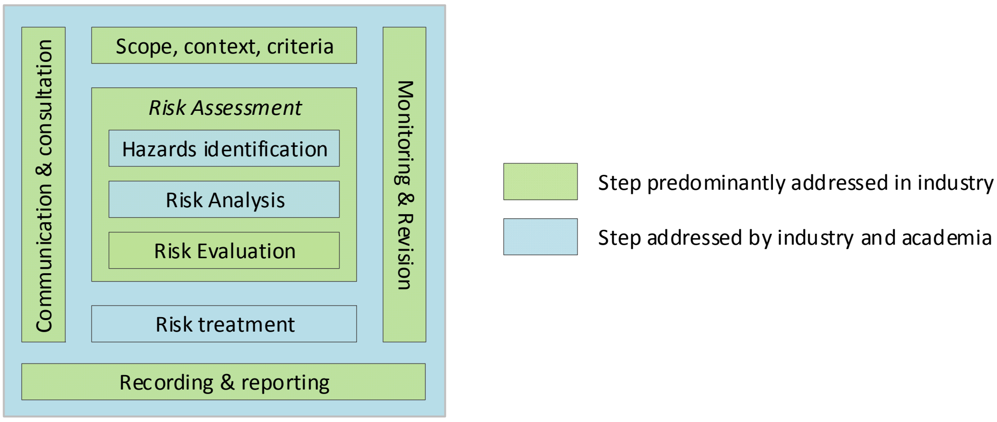

Figure 1: ISO 31000:2018 risk management process and its relation to education and practice

To ensure that University education provides students with the competency as process safety engineers, accreditation institutions such as Accreditation Board for Engineering and Technology (ABET) establish a set of outcomes in which safety is highlighted, with particular focus in hazards identification. ABET sets out 11 outcomes expected from a chemical engineering graduate, from which the (c) outcome relates to the design of a process meeting realistic constraints including health, safety and environmental. Although safety can be associated with all outcomes, this outcome is of particular relevance for educational purposes given that risk management begins with process design, which is usually overseen by chemical engineers. At the same time, risk assessments are initiated at early design stages and following through all the life-cycle of the operation, requiring the use of different input information and models that support calculations and estimations, such as gas dispersion modeling. Risk assessments results support the decision-making processes of the stakeholders concerning safety measures in operations, including land-use planning. Bringing all these elements together, risk assessment and the technical elements it involves constitute a central element of the responsibilities of a process safety engineers and therefore, of their education. Recent research (Goertlandt et al 2016; Rae 2012) has identified considerable uncertainty in the results of quantitative risk assessments (QRA) which is explained when analyzing each of its steps. The first step is a process hazard analysis (PHA), which allow identifying hazards and include a wide range of techniques, e.g., Hazards and Operability Analysis (HAZOP). In these analyses, different scenarios are analyzed to identify potential consequences and determined measures required to prevent, control and mitigate them. Researchers have presented that PHAs can miss up to 47% accidents occurring in facilities (Goertlandt, Khazad, Reniers, 2016), given the qualitative nature of these analyses and that, analysts do not know what they do not know. The second step is comprised of consequence and probability (or frequency) analyses, using inputs related to the operating conditions and characteristics of the facility. For consequence analysis of each accidental scenario, a wide range of models are used which differ in complexity, precision, and accuracy, all requiring competent users and adequate inputs. For probability analysis, different options exist including the use of qualitative descriptions, generic failure frequencies (e.g. OREDA) for design stages, probability distribution functions and the use of random sampling techniques such as Monte Carlo or (ideally) failure data from the facility.

The issues across each step of risk assessments are essential to explain the reported uncertainty and to throw light on the role of process safety education in addressing these issues. As Mannan (Mannan, 1999) stated about two decades ago, regulations and recommended practices are only an element in the solution to the safety issues an operation can face. The other element is the education received by engineers and in particular that these professionals understand the fundamental issues of implementing safety from the design and throughout the life-cycle of the operation. In light of the technical and human advancements achieved in the field of safety in these two decades and the improvement of chemical engineering curricula thanks to accreditations such as ABET, this paper presents a detailed picture of how complexity and uncertainty in risk assessments are addressed. The picture is presented in Section 2 and is based on a search for curricula and specific case-studies, as well as in the experience of the authors. Finally, a set of conclusions along with recommendations in Section 3, aiming at answering the following questions: 1) How can we better address uncertainty and complexity in risk assessments?; 2) How can we better convey the importance of risk assessment results in decision-making processes?; 3) What are the essential skills to be developed and what decisions do they support?

2. Complexity and uncertainty in process safety education

The starting point of this discussion is the fact that process safety is not part of all chemical engineering curricula across the globe. In the United States of America alone, only 23% of chemical engineering departments require Process Safety although this percentage is expected to grow as institutions adapt to requirements of accreditation entities such as ABET (Voronov et al., 2017). Furthermore, in the institutions in the US the credit average is 2.4 in institutions that directly address process safety, which is the lowest among all categories of courses; in Europe a parallel can be seen as the European Federation of Chemical Engineering (EFCE) recommends a 10% to 20% content in curricula, the lowest among all other categories. This means that safety does not constitute an integral element of the knowledge transferred to chemical engineering students in all education institutions, which in turn result in professionals with a gap in safety knowledge. This is a critical element of this discussion, since knowledge gaps are directly associated with the occurrence of incidents as pointed out by Krause (2016), and it is a reflection of epistemic uncertainty.
Examining undergraduate and Masters Curricula in Europe (Degreve, 2012; Brenig et al., 2013), it is noticeable that complexity is introduced to students by gradually transitioning from the use of process safety tools in simple systems to the considerations of its use in real systems. This is usually done through safety experts' lectures and the visit to real plants. However, the application of process safety tools to a real system – as most practitioners would recognize- requires considerable time and human resources that can often be unavailable at an educational level. This implies that complexity is introduced through examples and there is seldom explicit guidance to deal with a more complex (real) system. The challenge of recognizing complexity begins at educational environments, having as an example the lack of awareness of the hazards and associated risks with chemical laboratories operations. As presented by Olewski (2017), there is a "misperception that university laboratories are ‘low risks' and ‘inherently safer," which can be extended to small operating companies. This means that chemical engineers, process engineers and even educators in these fields fail to recognize and adequately deal with complexity. In summary, most curricula do not explicitly address a lack of safety knowledge, while the consequences incidents in university laboratories and small operations reflect the consequences of this epistemic uncertainty. It is noted that the responsibility for this lack of knowledge lays in both the educators and the students. For the latter, this lack of knowledge is an "unknown," and therefore they cannot manage it unless made aware of it. Eliminating these unknown unknowns is a task for more experienced and knowledgeable individuals, i.e., process safety educators, with the help of an explicit recognition of complexity and its impact on risk management. The role of education at University level and the need for its link with Industry is analyzed by Benitendi (2016), finding a need to construct a collaboration scheme that allows integrating process safety into chemical engineering courses. Constructing a compendium of courses such as those proposed by Benitendi might be unfeasible, given the challenges it presents to the educational staff and the commitment required by the industry. However, this proposal allows visualizing that the academia-industry link is essential to deal with the uncertainty inherent to process safety considerations, e.g., variable and unpredictable hazardous scenarios. This uncertainty or unknown unknowns appear again as a critical element to address by using industry's experience and the complexity a real setting has when compared to a typical educational textbook problem. Such element is also addressed by other educational initiatives for professionals, such as the one presented by Kennedy (Kennedy et al. 2015) in which a course is constructed by academia to respond to the process safety knowledge gaps of a particular operation. In this course, one of the specific objectives is to "enable staff to recognize and challenge uncertainties". Although the course itself addresses the knowledge gap, the contents of the course do not explicitly address the uncertainty involved in process safety studies and their impact on decision-making.
Given that effectively supporting decision-making is the end goal of risk assessment, the role of complexity and uncertainty is embedded in a broader context. This context is presented in the form of a flowchart in Figure 1, where the key stakeholders involved in risk management converge. In particular, it can be seen the crucial role of academia as it educates and trains professionals. Process safety education uses the previously mentioned curricula and courses, but can easily omit the underlying uncertainty and complexity of operations, which result in failures and unacceptable loss. Explicitly recognizing the role and importance of these two elements is a challenge given the limited resources in academia; however, the authors believe this can be gradually overcome.

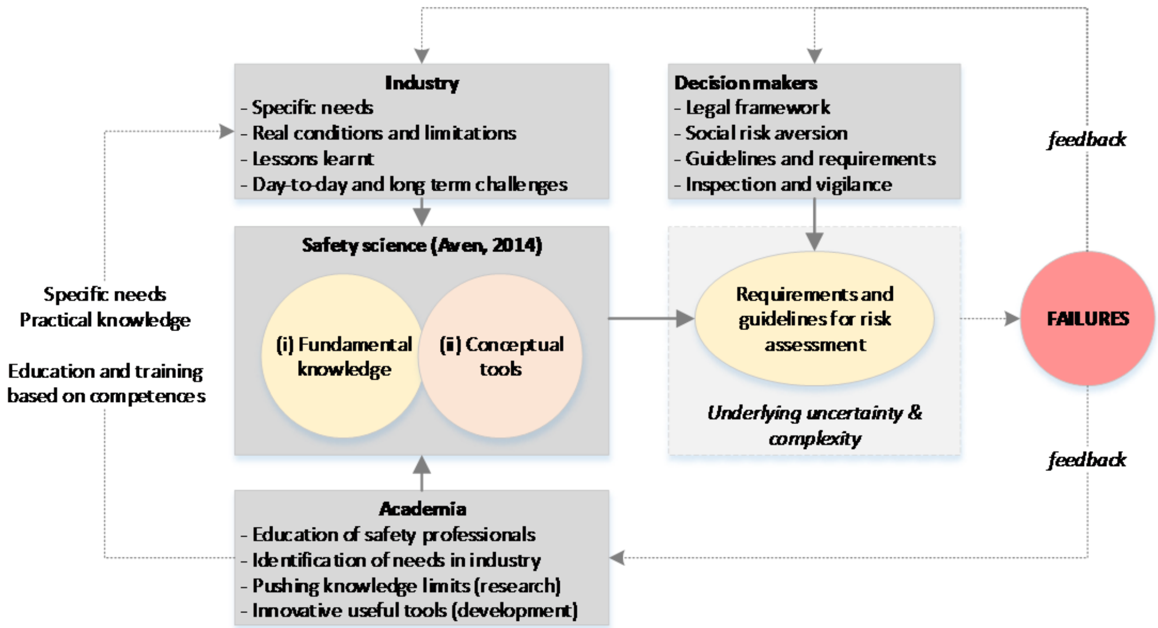

Figure 1. Flowchart of Safety Science construction and its relation with key stakeholders

3. Conclusions and recommendations

This review briefly presents a picture of the current role of complexity and uncertainty in process safety education, through selected examples of curricula and particular courses. This shows that complexity is a fundamental element of process safety education, as of chemical engineering, depicted by the use of simplified examples and then by more complex case studies.

Furthermore, it was found that examples exist in which the link between industry and academia allow to take this case studies even further and provide students with real-life conditions and limitations, which has a direct effect on their formation as competent safety engineers. The review also allowed constructing a flowchart for knowledge in the form of Safety Science, as per the definition provided by Aven (2014). This picture shows the complexity behind the proper education and training of safety engineers, requiring all stakeholders to be directly or indirectly connected (e.g., society through the acceptability criteria defined by regulating bodies) and the need for continuous feedback from failures. Based on this flowchart and the typical contents of the reviewed curricula, the authors notice an absence of explicit reference to the uncertainty sources that can considerably affect the results of a risk assessment and therefore the following decision-making process. The omission of uncertainty in process safety education can be as potentially dangerous as the omission of process safety contents from a chemical engineering education. Based on the own experience of the authors in risk assessment and management projects with the government and the private industry, as well as on the typical contents of process safety programs, a list of uncertainty sources was formulated. This list is used to formulate a series of suggestions that should help educators to consider them. Here, the goal is to provide students (regardless of the level of formation) with additional tools to understand process safety not as a checklist of studies, but as an activity in which uncertainty and complexity are always present. By explicitly recognizing uncertainty and providing the students with the currently available tools to deal with it, decision-making in the chemical process industry can be enhanced. Taking the previous into consideration, to answer the questions: *How can we better address uncertainty and complexity in risk assessments?* and *How can we better convey the importance of risk assessment results in decision-making processes?*, the authors make use of the typical contents in process safety education. These topics range from hazards characterization to risk communication. Table 1 presents the sources of uncertainties and the associated suggestions for each one of these topics, as well as examples of successful applications. Education institutions should consider this during the construction of process safety programs and by educators for the design of syllabus.

Table 1: Uncertainty associated to process safety education

Topic	Sources of uncertainty	Suggestions
Hazards characterization	Availability of thermodynamic and hazardous properties Availability of data for mixtures Complexity of process conditions e.g. multiphase systems	Emphasis during fundamental courses of chemical engineering on the weaknesses present in thermodynamic data generation, both in equipment and interpretation
Hazards identification	Completeness of operation information Availability of accepted guidelines for executing techniques Multi-disciplinary nature of workshops Participants expectations and interests Participants' personalities Presence of *unknown unknowns* (e.g., failure modes) Impossibility of managing *unknown unknowns*	Run of workshops in which hazards identification techniques are exemplified using real-life case studies, such as those investigated by the Chemical Safety Board of the U.S. Noakes (Noakes et al. 2011) provides an example of an innovative module for HAZOP education, consistent with these suggestions.
Risk analysis	Definition of risk	The definition by Kaplan (1981) set the foundation for QRA. This is not the only definition available (Aven, 2009), and students should be made aware of this.
Consequence analysis	Completeness of thermodynamic data for calculations for mixtures Availability of modeling options and the assumptions that support them Degree of model validation Technical competencies for model selection, use and results interpretation Sensitivity of results to model parameters and assumptions	Run of simple scenarios using a wide range of tools, e.g., use of the TNT equivalence model, TNO multi-energy and Computational Fluid Dynamics codes for comparing overpressure of a vapor cloud explosion.
Probability of failure	Available knowledge regarding failure modes and dependency between them Availability of data to select parameters for the probabilistic distribution Availability of data/frequencies for specific system's conditions Sensitivity of results to model parameters and assumptions	Given the importance that scientists, practitioners and regulating bodies give to probabilistic analysis, the limitations on defining limit state functions and the use of probability distribution functions should be provided.
Risk evaluation	Nature of criteria: prescriptive, consequence-based, individual risk, societal risk Availability of guidance to use and interpret acceptability criteria Sensitivity of evaluation to risk analysis parameters and assumptions	Use of publicly available quantitative risk assessments to show the consequences in the decision making of using internationally differing criteria for individual and societal risk (Pitblado et al. 2012)
Risk treatment	Completeness of current safety barriers, e.g., BowTie Cost-benefit limitations Organization's internal guidance and accepted safety measures	Provide examples of successful implementation of safety barriers, using case studies of industry. In case this link is not available, use examples of daily life to exemplify the selection of safety measures under cost and time constraints.
Risk communication	Completeness of stakeholders' identification and characterization, including their expectations and risk aversion Availability of communication guidance that supports the use of risk assessment information	Invite regulating bodies and industry's representatives that can present the importance of the risk management decisions that are taken, and how the role and competencies of the safety engineer directly affect these.

Regarding the skills of a process safety engineer, Beard (2005) stated that a knowledgable user is one of the three elements required for an acceptable use of a model in fire safety engineering; the other two being a model and the methodology to use it. Beard defined a knowladgable user as that "Who is capable of employing the methodology to a model which has the potential to be valuable in a particular case in a comprehensive and explicit manner, and interpreting results justifiably". This is a challenge, as Beard (1996) had previously stated using an example for a temperature calculation, in which the associated errors with it are the assumptions made, the numerical errors, software and hardware malfunctions, and the application errors. The reality is not different even for a simple overpressure calculation using the TNT equivalence model. Furthermore, the Center for Chemical Process Safety establishes competency as one of the 20 elements of the Risk Based Process Safety model. This is presented in CCPS (2010) as one of the key elements for process safety commitment pillar, where a general framework for maintaining competency in the industry is presented. However, this framework does no state the relevance of explicitly addressing uncertainty in the course of process safety tasks.

To the question of what are the essential skills to be developed and what decisions do they support? The authors believe that the capacity of safety engineers to recognize their limitations in knowledge and tools, especially for complex systems, is key to achieve a continuously better risk management. Recognizing there are unknown unknowns over which no feasible control exists besides permanent monitoring and an explicit consideration of assumptions, is essential. This brief review and the considerations presented regarding treatment of uncertainty in process safety education, an sets the foundations for further work.

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