Perspective

Trends and Challenges in Process Safety

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Introduction

Process safety engineering is the science of implementing into everyday engineering procedures a broad-based understanding of the complex interaction of chemical process technology, mechanical and process design, process control, and process safety management systems. Chemicals play a key role in today's high-tech world. The chemical industry is linked to every technologically advanced industry, and only a handful of the goods and services we enjoy on a daily basis would exist without essential chemical products. However, the use of chemicals is a two-edged sword. Safe use creates a healthier economy and a higher standard of living. Unsafe use threatens our lives, our businesses, and ultimately our world.

Process safety is very closely linked to sustainable development. Engineering research in the 21st century needs to bring together elements of manufacturing, design, and sustainable engineering in an integrated form. Interwoven through this new paradigm is the consideration of risk in every aspect. An engineer must function as a member of the global community. This means not only competing in the global marketplace but also acting as a professional who shares global responsibilities. These responsibilities entail a proper accounting of finite world resources, a sensitivity to the impact on the environment, ethical conduct, process safety, risk consideration, and much more. This much needed aspect of sustainability to engineering education, research, and practice can be summarized as the design of materials, processes, products, and systems to sustain good and safe conditions for human health and the environment.

Over the last 30 or more years, many catastrophic incidents have captured the attention of the public and the media. Companies cannot be sustainable without successful safety and risk management programs. Thus, by extension, it is impossible for society to reach the goals for engineering for sustainable development without successful safety and risk management programs. Our inability to adapt to the demands of a changing world and ecosystem has the potential to take us down the same path as the dinosaurs. In that respect, systems engineering and analysis of complex systems have the potential to identify and solve some of the process safety challenges.

The first mention of systems safety started after World War II, as technology quickly developed and engineers were faced with an increased level of complexity for the new design of facilities or technologies. In the 1950s and 1960s, frequent and unexpected failures were experienced by the American missile and nuclear programs, and parts of these failures were found to be due to deficiencies in the design, operation, and management. Therefore, the intercontinental ballistic missile system was developed and was known as one of the first systems to have a formal, disciplined safety program. At the same time, the US Air Force was also experiencing major losses of aircrafts and pilots and developed the first systems: wide safety specification BSD Exhibit 62-41, which was a safety engineering system for the development of air force ballistic missiles. The military also developed a standard for system safety, which was revised further in 1969 and published as MIL-STD-882, the requirements for a system safety program for systems and associated subsystems and equipment.[1]

The military standard considered the foundation document for system safety is still used by the US Department of Defense after many revisions, and this suggests that safety must be viewed in a system perspective.[2] In this Perspective, we aim to prevent incidents and mishaps; protect the system and its users, the public, and the environment; identify, eliminate, or control hazards; design and develop a system with minimal risk; and create a safe system by intentionally designing safety into the overall system. The system safety process involves the system safety program plan, hazard identification, risk assessment, risk mitigation and verification, risk acceptance, and hazard tracking, as shown in Figure 1.

The failures in the aerospace and defense industry in the last decade initiated a systemic approach for preventing incidents.[4] Leveson[5,6] stressed on the necessity of considering the functioning of the system as a whole instead of focusing on the functioning of the individual parts of the system to prevent its failure. Leveson's work considers safety as an emergent

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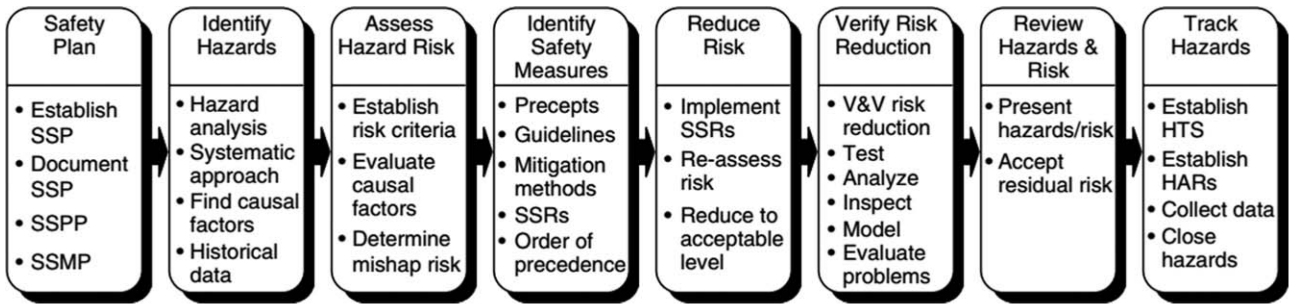

Figure 1. Core system safety process.[3] Reproduced with permission from "Hazard Analysis Techniques for System Safety" by Ericson, CA (2005). SSP: System Safety Program; SSPP: System Safety Program Plan; SSMP: System Safety Management Program; SSRs: System Safety Requirements; V&V: Verify and validate; HTS: Hazard Tracking System; HARs: Hazard Action Records.

system property and safety measures as system constraints on the behavior of the system. To this effect, Leveson developed new concepts, such as system theoretical accident model and system theoretical process analysis on the basis of the philosophy that components of a system can be safe, but the interaction between them may not be, and therefore, a high reliability of the components does not guarantee the reliability of the system.

Venkatasubramanian[7] also advocated a systemic approach be applied to the process industry and listed many challenges for the systems and chemical engineers; these included technological, personnel, procedures, management and culture, regulatory, and conceptual challenges. To further elaborate on these challenges, he suggested that a prognostic approach is needed to predict the problems in managing systemic risks.

The military approach has inspired many books on system safety engineering.[3,8] These books profess that hazard analysis has to be performed not only at the subsystem level but also at the system level and should focus on the interfaces and safety critical functions. The book by Ericson[3] focuses on providing tools for hazard analysis and dividing hazard analysis into different categories (preliminary design phase, design phase, operation phase, and support phase), which depend on the phase of the project in which the hazard analysis has to be performed.[3] Bahr[8] covered the entirety of the system safety process and went a step further in describing some process hazard analysis techniques, such as what-ifs, checklists, hazard and operability (HAZOP) studies, failure mode and effect analysis, fault tree analysis, management oversight risk trees, energy trace and barrier analysis, sneak circuit analysis, and cause-consequence analysis. This book also compares all of these techniques by application, life-cycle phases, time requirements, skill levels, and cost and concludes that one technique is not better than another but will depend on the objectives and needs of the industry; it also concludes that several techniques can be combined in the form of a tool box.

Beyond this, a systems thinking approach should also include software in the analysis.[8] The same conclusion was also provided by a review of hundreds of accidents and incidents related to software.[9] The main lesson learned from the incident reviews is that software is often not included in the organization risk and hazard analysis and is not effectively incorporated in their process safety efforts. In all of these references, the need to include a human in the loop of a system safety process was emphasized but not precisely detailed.

This view of system safety is mostly an update of current risk assessment and management practices and does not really reflect a true systems approach. In their book about engineering systems, de Weck et al.[10] summarized the concept behind what they called *(re)thinking about systems*. The first important principle behind thinking about systems is that one must always have a multidisciplinary view of the system by changing view angles but also changing the viewpoint by considering different levels of detail. Four fundamental perspectives should be considered—scope and scale, function, structure, and temporality—simultaneously from the technical and social perspective. The function is the action for which a system is specially fitted or used or the reason for which the system exists. The scope and scale defines the boundary of the system. The structure refers specifically to the way in which the elements of the system are interconnected, but architecture is a broader concept that also includes the assignment of subfunctions to the elements of the system. Finally, a system is dynamic, and the effect of different timescales, from minute to decades, also needs to be specified.

Coming back to system safety as currently defined, the function, which is risk assessment and management, is defined. The temporality is present because different methods for hazard identification exist for different phases of a project, together with a structure, because different risk assessment methods are defined for system and subsystems. However, these principles are mostly applied from a technical point of view with very little emphasis on the social perspective, and more could be done for the temporality and structure perspectives. In this article, a new process safety system is proposed. The current principles of risk assessment and management need to be viewed from different viewpoints: engineering and science, life-cycle analysis (LCA), and safety culture and climate, as summarized in Figure 2, with the risk assessment and management being performed with the final objective of sustainability.

Science and Engineering

Catastrophic process safety incidents continue to occur, despite advances in the understanding of the underlying causes over the years. Process safety deals with the avoidance of these incidents caused by the release of hazardous substances

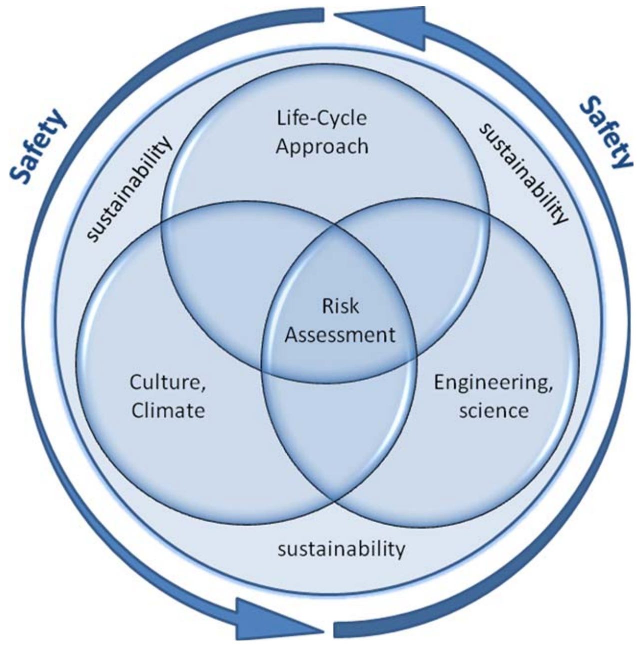

Figure 2. Process safety system.

in continuous, semicontinuous, or batch industrial processes. In addition, process safety is also applied to the storage and transportation of hazardous materials. If we take a close look at the lessons learned from these incidents, the inevitable conclusion is that most of these incidents could have been avoided through a better understanding of the fundamental science and engineering behind the processes at hand.

Because the goal of process safety is to prevent harm due to loss of containment of hazardous substances, it is essential to predict potentially disastrous scenarios, the degree and extent of damage associated with a scenario and the actions necessary to prevent them, and to reduce the consequences if an undesirable scenario was to occur. This includes understanding all of the possibilities by which a process can derail and the probability and consequence of each scenario. In view of this, process safety can be tied to a large number of disciplines of which the particular fields include computing and instrumentation, statistics and reliability engineering, psychology and organizational science, construction design and engineering, equipment, systems, and controls.[11] However, to predict the scenarios, we need to gain a fundamental understanding of the science, which can be obtained by a literature review and experimental and computational studies. As an example, the reference book *Chemical Process Safety: Fundamentals with Applications*[12] contains 16 chapters, and 13 of them are dedicated to engineering or science principles, such as reactive chemicals, dispersion modeling, and toxicology. The other three chapters are dedicated to hazard identification, risk assessment, and case studies. Another reference for process safety is *Lees' Loss Prevention in the Process Industries,* where the majority of the 40 chapters are tied to engineering or science principles.[13]

Kumamoto and Henley,[14] in their book Probabilistic Risk Assessment and Management for Engineers and Scientists, explained conceptual and methodological treatments and clarified how to satisfy safety goals by Probabilistic Risk Assessment (PRA) to be complemented by deterministic approaches, such as defense-in-depth and good engineering practices. An algorithm was developed by Lapp and Powers[15] to draw fault trees, which could handle complex systems efficiently and considered topology, multivalued logic, and consistency checks. Leveson and Stephanopoulos[16] presented a system, a theoretical and control-inspired engineering approach to process safety, to the scientific community. Venkatasubramanian and coworkers[17,18] have published many articles on early fault detection and diagnosis, which can help prevent abnormal event progression. They suggested the use of a predictive approach to develop real-time intelligent support systems that can effectively monitor key parameters of process operations and detect and diagnose problems. These systems should be able to notify operators and engineers about incipient abnormal events. Such predictive systems can also be invaluable in the design stage, where they can be used in the identification of potential hazards in the proposed design. However, to be successful at this endeavor, there is a need to address the conceptual challenge of being able to predict the effect of these changes or interactions under various conditions and how these will propagate through the entire complex engineered system.[17,18] A lack of understanding of engineering or science during the different phases of risk assessment can lead to incidents. Some examples of recent major incidents are presented here; these could have been avoided if fundamental science and engineering would have been used to understand the scenarios better.

The US Chemical Safety and Hazard Investigation Board identified 167 serious reactive chemical incidents in United States from 1980 to 2001; these resulted in 108 fatalities and losses of hundreds of millions of dollars.[19] A review of major reactive chemical incidents,[20] such as those at Napp Technologies (Lodi, NJ, 1995, five fatalities); BPS, Inc. (West Helena, AR, 1997, one fatality); Morton International, Inc. (Paterson, NJ, 1998, nine serious injuries); Concept Sciences, Inc. (Allentown, PA, 1999, five fatalities); Whitehall Leather Co. (Whitehall, MI, 1999, one fatality); and BP Amoco Polymers (Augusta, GA, 2001, three fatalities), advocated that fundamental concepts should be applied and fully understood to prevent such incidents in the future. An extensive literature survey of fundamental thermochemical calculations (e.g., oxygen balance, heat of reaction, maximum pressure/rate of pressure rise, adiabatic temperature rise, reaction rate constant), computer programs (CHETAH), screening tests (e.g., differential scanning calorimetry, thermogravimetric analysis, mixing calorimetry), incompatibility tests, and sophisticated tests (e.g., adiabatic and reaction calorimetry) should be performed to gain a better understanding of the hazards. Apart from experimental methods, computational methods, such as quantum mechanical models and correlations, can be used to understand the behavior of reactive chemicals at the molecular level under different operating conditions and also in the presence of contaminants.

The Buncefield incident, which occurred on December 11, 2005, was caused by the overfilling of a tank because of a problem in the tank gauge. This caused the release of 300 metric tons of gasoline; this created a flammable vapor cloud that ignited and created a major explosion, which was succeeded by other explosions that damaged property in a 10-km radius and injured more than 40 people; this incident became one of the largest peacetime explosions in Europe in the last 50-60 years.[21] One of the more effective methods for preventing vapor cloud

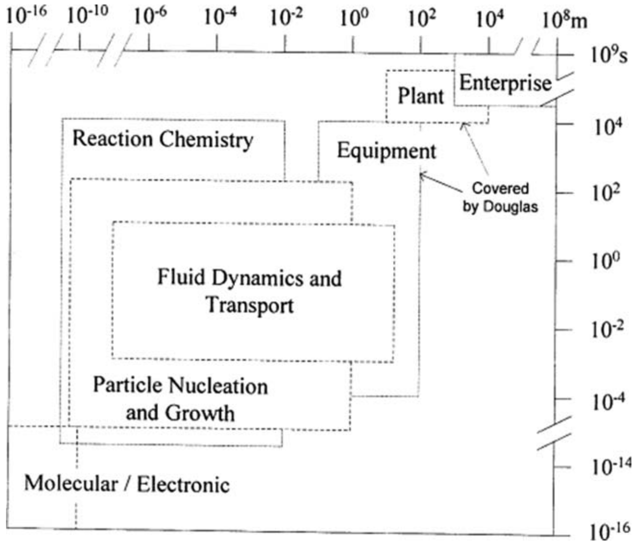

Figure 3. Length and time scales of multiscale objective-oriented process development.[24] Reproduced with permission from "Beyond process design: the emergence of a process development focus" by Ng KM, Wibowo C (2003).

explosions is the prediction of the occurrence of explosions and their impact through proper analysis of overpressures that can possibly develop in the course of a vapor cloud explosion. Vapor cloud explosion overpressure prediction methodologies vary from simple empirical models to more sophisticated phenomenological models and complex computational fluid dynamics models. The Buncefield incident resulted from a complex phenomenon that is still not fully explained in many publications.[22] The scenario reflects a low probability of a combination of events that was not considered in the hazard identification conducted during the safety reports; this was due to two wrong assumptions that were related to the physical comprehension of vapor cloud explosions; a Vapor Cloud Explosion (VCE) in an oil depot was not considered a credible event, and a VCE was presumed to require a high level of containment. In their analysis of the Buncefield incident, Paltrinieri et al.[22] concluded that this low-probability combination event was facilitated by technical, human, organizational, and societal factors and that only a holistic approach to risk would improve the prevention of such incidents.

There is a need for a systematic management approach that incorporates the fundamental concepts of hazard identification, hazard evaluation, and hazard control throughout the process life cycle. In addition, more research is needed in the comprehension of hazardous phenomena; this was identified as the first topic in the process safety research agenda for the 21st century[11] and will help both as a preventive effort and also in the design of protective measures. More research on explosions is needed, especially for stratified clouds, hybrid mixtures (gas and dust), and flame acceleration processes, especially the deflagration-to-detonation transition. With regard to chemical reactivity, more research is needed to further improve the thermal stability and decomposition of materials by improving the models and having a more precise determination of the induction periods or the sensitivity of chemicals to various stimuli. The analysis of the ability to estimate the heat-release rate of energetic materials indicates that corrections are required in all calorimetric methodologies.

The application of multiscale approaches is garnering the attention of engineers and scientists now more than ever, as it helps in the modeling of systems from different viewpoints.[10] Any system can be described by models of various complexities.[23] Most of the time, coarse-grained modeling is sufficient, except in some small regions that require more detailed modeling. The modeling hierarchy depends not only on time and space scales but also on the phase of the material to be studied. The challenges of multiscale modeling are to understand the physical models at different scales, how different complexities are related, and also how to formulate mesoscale models, that is, models at intermediate levels of complexity.[23]

The multiscale objective-oriented process development approach goes further in scale for time and space,[24] reaching from the molecular level to the scale of a company, as illustrated in Figure 3. The idea is that the objective at the enterprise level (which in this article, is to maximize the shareholder value added) should be shared by plant personnel and researchers and redefined into technical objectives that drive the lower scales. The framework idea of vision sharing and collaboration among all employees can be applied with a goal of safety and should drive all scales of a process.

Liquefied natural gas (LNG) facility safety is a good example of such a multiscale problem. As a cryogenic liquid, LNG forms a liquid pool and generates a vapor cloud once it is leaked onto the ground or into water. To determine the consequences of a catastrophic LNG spillage is critical for risk assessment; however, the vaporization of LNG and the vapor dispersion process are also complex problems. Process safety issues in an LNG facility at different scales, molecular, mesoscale, and macroscale, are shown in Figure 4.

LNG is a mixture mainly composed of methane and a small amount of ethane and other higher hydrocarbons. The LNG vaporization process is determined by the thermodynamics of LNG at the molecular level, which are dependent on the LNG composition. The boiling of LNG depends on the LNG composition and its thermodynamics on the molecular scale, the bubble pattern around the hot surface in the mesoscale, and also the flow of liquid on the macroscale. The boiling phenomena on the mesoscale can also affect the flow conditions of LNG during the pool-spreading process on the macroscale.

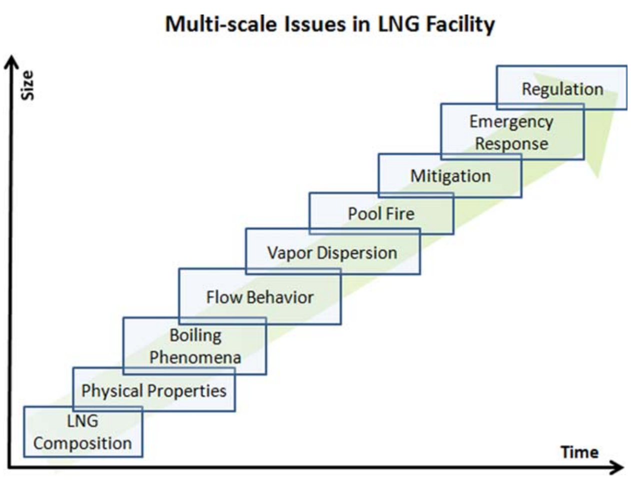

Figure 4. LNG facility safety concerns in multiscale.

Although vapor dispersion, pool fire, and mitigation are plant/facility scale processes, the fundamental understanding of their behavior is directly related to what is happening on the mesoscale and molecular scale.

A multiscale approach may provide an efficient and systematic solution to the safety issues of LNG facilities. For example, the prevention of an LNG pool fire requires the knowledge of methane combustion chemistry, mass and heat transfer, and air turbulence on different scales. LNG pool fires are also function of heat radiation to and absorption by the LNG pool. A systematic multiscale approach for modeling the pool fire should be efficient and could lead to optimized solutions, for example, mitigation methods could be developed in different scales to control or reduce pool fire hazards.

LCA for Sustainable Development

As stated previously, systems are dynamic, and it is important to consider small but also very large timescales in the analysis. The consideration of large timescales involves the consideration of the whole life cycle of a plant or a process and the safety related to it, but on a larger timescale, it is also important to consider the sustainability of a plant or a process for future generations.

LCA and safety life cycle

LCA, also known as life-cycle assessment, cradle-to-grave analysis, and ecobalancing, is a technique for assessing the environmental aspects and potential impacts of a product, process, or service with all of the stages of a product, process, or service from cradle to grave (e.g., from raw material extraction through materials processing; manufacturing; distribution, use, repair, and maintenance; and disposal or recycling).[25,26] In the 1990s, the Society for Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO) started to work on defining LCA and developing general guidelines and principles for LCA methodology.[27–29]

As defined by ISO, LCA is a compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle.[28–30] The methodology framework developed ISO includes four major stages for conducting LCA: goal and scope definition, which sets the boundary of the analysis; inventory analysis, which lists the input and output of the system defined in the scope and collects data necessary for these input and output; impact assessment, which goes deeper in the understanding of the environmental significance of the previous stage; and improvement assessment and interpretation, where the results of the last two stages are discussed according to the scope of LCA.[27,28,31–33]

However, even with an ISO standard, LCA has its drawbacks. First, as with all system thinking approaches, LCA requires one to set a boundary for the analysis but this boundary is sometimes left to the appreciation of the company and can differ greatly from one analysis to another.[34] In addition, LCA is very complex and requires extensive knowledge and an extensive amount of data; the analysis requires the need for simplification while staying scientifically acceptable so that LCA can be applied in any stage of a process but can also be integrated in other areas, such as business design and strategy. Finally, LCA focuses on environmental issues, so it would be beneficial to have a wider scope that could encompass other dimensions of sustainability, such as social, economic, and safety.[34,35] Researchers have already started to work on issues raised in the preceding text. In the area of extending the scope of LCA, studies have shown that LCA can be applied as a tool for process design by helping in decision making by adding the environmental point of view.[25,30]

Although LCA focuses on the environment, life-cycle thinking has also been applied in the area of safety. Life-cycle thinking applied to safety has already been implemented in standard IEC 61508, which defines the *safety life cycle* as necessary activities involved in the implementation of safety-related systems and occurring during a period of time that starts at the concept phase of a project and finishes when all of the Electrical/Electronic/Programmable Electronic Safety-related Systems (E/E/PE) safety-related systems, other technology safety-related systems, and external risk reduction facilities are no longer available for use. Figure 5 shows the overall safety life cycle proposed by IEC 61508. A safety life cycle also starts with an initial concept phase and progresses through design, implementation, operation, maintenance to modification, and finally decommissioning.[36]

More recently, the idea of embedding inherent safety into the safety life cycle has received a lot of attention.[37] Hurme and Rahman[37] discussed the life-cycle phases of a process (conception of the idea, research and development, preliminary process design or pre-engineering, basic engineering, detailed design and construction, operation, maintenance and modification, and decommissioning) and the possibilities of implementing inherent safety in each phase. They also evaluated the applicability and accuracy of the Inherent Safety Index to the life-cycle phases of the methyl methacrylate process. During the life cycle of the process, the opportunities for making changes in the process first increases until the basic engineering design of the process, after which it starts to decrease. In the idea phase, typical information on a new process is the reaction chemistry and the basic properties of the compounds. The result of inherent safety estimation by index methods in this phase is very rough and does not provide the correct ranking of the process. In the research and development phase, the main goals are yield, product quality, and safety. In this phase, the designer has the greatest opportunity to apply inherent safety by choosing the best and safest chemistry, scale-up method, and process intensification. This is also the best phase in which to apply safety indices because all of the information needed is available. In the process predesign phase, decisions related to preliminary layout, location, dimensioning, and unit operations are made. In this phase, the intensification, simplification, and attenuation of operating conditions can still be performed. Index-based approaches can be applied, although there might not be much change from the conceptual phase. In the basic engineering phase, piping and instrumentation diagrams are drawn, and the inherent safety aspects in this phase relate to piping, instrumentation, and equipment. Here, more detailed studies, such as HAZOP studies, are more suitable than inherent safety indices. In the phases of detailed engineering, construction and startup, operations and maintenance, and decommissioning, any changes to the process would be expensive, and so add-on safety measures take over. In these later phases, human error becomes

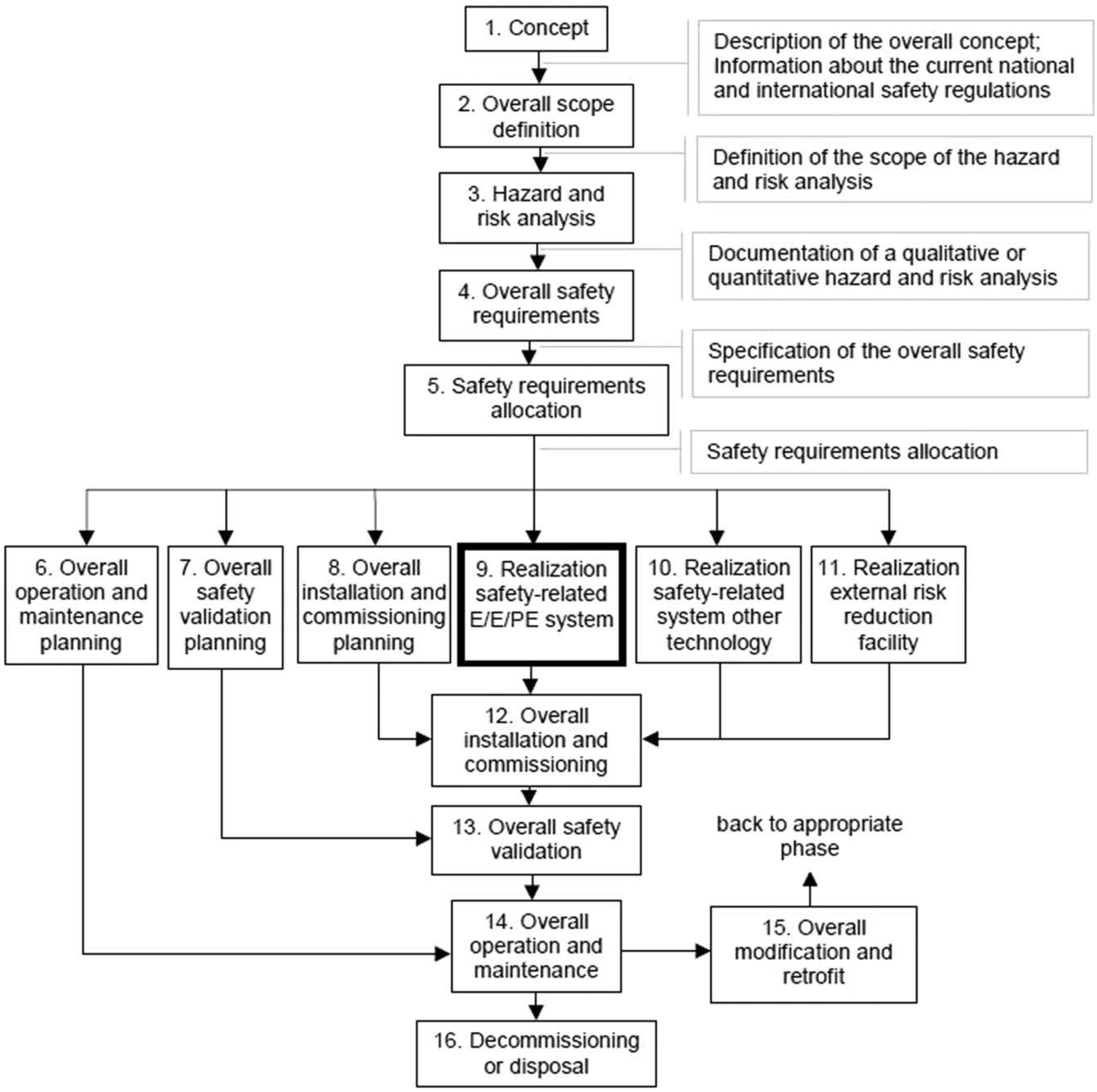

Figure 5. Overall safety life cycle (adapted from IEC 61508, 2003).[36]

more important, and therefore, the design in the preliminary stages should be tolerant to these errors. The degrees of freedom for the decision for inherently safer process design continuously decrease as we proceed through the life cycle.[37]

The purpose of the safety life cycle is to optimize the process design and enhance the safety performance of processes. This approach could be applied to different design processes with the same fundamental steps: problems are identified and assessed, solutions are found and verified, and then, the solutions are put into use to solve the problems. In view of this, the understanding of life-cycle issues and the implementation of process safety options in consideration of those issues has many merits. It could make a plant safer with low systematic errors, and it could decrease the cost of engineering and increase the process uptime. It could also lower operation and maintenance costs greatly through the selection of the right technology. For all of these reasons, the safety life-cycle process is very essential for the purpose of improving the reliability and productivity of facilities and plants.[38]

Safety LCA is still mostly restricted to safety-instrumented systems.[39] Recent research has looked to apply safety life-cycle models in process safety management to obtain a *safety life-cycle management*, defined as "the integral control of the safety management activities with regard to all phases of the safety life cycle. The control is based on the application of a structured safety life-cycle model, which is the framework on which the safety management system is established Knegtering, Berend (2002)."

Design stage

There is a significant rise in the risks posed by the chemical industry to life, the environment, and property because of problems and deficiencies in design.[40] Major equipment-related incident cases from the Failure Knowledge Database were analyzed to determine the design errors in the chemical process industry. This analysis exposed the role of design in incidents: 79% of the incident cases analyzed were contributed by design errors, which was substantial. The most critical design errors were poor layout (17%), inadequate concern for chemical reactivity and incompatibility (16%), and incorrectly chosen process conditions (16%). The design errors were introduced at the basic (32%), detailed (32%), and preliminary (22%) design phases of the project. This analysis also showed that errors in the fundamental aspects of chemical processes, such as route selection, were more severe compared to other error classes.

In chemical process industries, safety is usually considered by two methods: the conventional method and the inherent safety method. The conventional method, or extrinsic safety, uses procedural (administrative) controls and additional safety devices at the end of design to take care of the hazards identified during hazard analysis. These safety devices are intended to perform in case a process upset occurs that could lead to a loss of containment. This can complicate the design and lead to additional costs in the later stages of design.[41] These traditional methods used to analyze safety hazards can be used qualitatively or quantitatively. Qualitative methods include the what-if, checklist, preliminary hazard analysis, and HAZOP methods, which are used to evaluate and identify hazards both at the early design and operating stages.[42] These methods are relatively simple to use and understand as they are based on brainstorming techniques or a set of questions related to the process and are generally developed by experts from process industries.[43] For complex design, a quantitative method, such as quantitative risk assessment, is used to support decision making, and in this case, detailed technical information is very important in the performance of the assessment. Even though precisely quantified solutions are identified, this method is still dependent on subjective judgment and does not address all safety issues for the plant.[44] More often than not, safe design options are identified at a much later phase of the design, and any proposed changes are very expensive.[45]

The inherent safety method involves the elimination or reduction of process hazards through the use of inherent properties of materials or processes and process equipment.[46] The major principles of inherent safety are intensification, substitution, attenuation, limitation of effects, and simplification. These principles help evade or reduce hazards with benign materials and operating conditions, minimizing inventory, and through the design of a simpler and user-friendlier plant. The early design stages present better opportunities for the identification and development of inherently safer process alternatives for solvents, reaction paths, and catalysts.[42] Enhanced productivity and public reputation, reduced life-cycle cost, better reliability, reduced company liabilities, and improved safety and environmental performance are some of the paybacks of the industrial application of inherently safer technologies. As stated by Kletz,[47] inherent safety aims for the elimination or the reasonably practicable reduction of the hazards in a system. The main notion of this approach is that a truly inherently safe system cannot possibly fail. This reverses the requirement for safety devices to reduce the risk of incidents (likelihood and/or consequences) to acceptable levels. Inherent safety is usually considered in relative terms as hazards cannot be completely removed in the process industries, but inherently safer designs open up new opportunities for realizing this goal. The application of inherently safer systems can considerably reduce the high costs usually associated with the full plant life cycle, from hazard management to regulatory liabilities and safety system maintenance.[48] However, inherent safety options must be considered with a holistic analysis to prevent unintended consequences, such as risk transfer and risk accumulation.

A review on the progress of developments in inherent safety during the period 2001-2011[49] included a survey of articles published on inherently safer design and organized them on the basis of risk, which included hazards and the likelihood of their happening and the way in which inherent safety was understood or assessed. The authors observed that hazards received the attention of 87% of the articles, and the distribution of the article subjects was materials (29%), chemistry (22%), unit operations (14%), flowsheet and layout design (28%), and storage and transportation (7%). They showed that the estimation of material properties, especially flammability, explosivity, and reactivity, have received significant attention during this 10-year period. This knowledge could help chemists and engineers understand the inherent hazards of a process and further in the choice of benign materials. Also, the design of novel reactor systems, such as microreactors and reactive distillation units, has gained considerable understanding and development. However, the study of domino effects and inherently safer layouts of chemical plants has occurred predominantly in the last 5 years. This study also brought to light a major issue that is covered in only a small amount of the literature on understanding human factors from an inherent safety perspective.

Current safety assessment methods used for the evaluation during the process design stage are mostly index-based methods, such as the Prototype Index of Process Safety[50] and Inherent Safety Index.[51] Index-based methods are simple to use, as they limit the set of effects of a process with subjective scaling and subjective weighing in scoring subindices. Researchers and scientists have attempted to incorporate the effect of domino effects and the life cycle of process design with many different approaches to improve the performance of the indices, but there are many shortcomings of index-based methods, one of which is scaling. In scaling, physical or chemical properties are divided into subjective ranges with each range assigned subjective scores potentially biased by human judgment. Another shortcoming from subjective scaling is discontinuity at the subrange boundaries.[52] The assessment methods have made further advancement through the incorporation of design simulators and through a risk-based approach. Incorporation of process design simulators is helpful in designing inherently safer design processes. The current trend in safety assessment methods seems to be moving toward a risk-based approach with advanced techniques with less reliability on human judgment.

Inherent safety is not routine yet. However, inherent safety and the implementation of inherently safer options continues to be the subject of passionate and extensive debate and discussions. The application of inherent safety concepts can create the issue of trade-offs, and reactive distillation is a classic example of this tradeoff.[53] The application of inherent safety professes simplification of the processes, which could be done by the intensification of two processes into one, but this may lead to complexity. Khan and Amyotte[54] categorized inherent safety barriers into four general types; these included (1) timing for individuals at different career stages, degrees of exposure to inherent safety principles, and project life cycles; (2) tools for various stages of plant, facility, or operation life cycles; (3) trade-offs within the suite of inherent safety principles; and (4) overall risk reduction measures (i.e., inherent, engineered, and procedural) and training at the developmental (undergraduate) and professional stages. Inherent safety can be made routine through continued training and promotion of inherent safety principles to companies, universities, and practicing engineers; the promotion of inherent safety principles to smaller companies who might be unaware of these principles; the promotion of inherent safety principles to the process development chemists who work on the chemistry of the process early in the life cycle; and the support of research to devise alternate, safer process chemistry routes. Inherent safety principles can be promoted by improved regulation, education, economic analysis, integration with green chemistry, and integration with security management[55] to make it routine. Similar conclusions were also drawn about challenges in the implementation of inherent safety principles and the way forward in a white paper published by the Mary Kay O'Connor Process Safety Center.[56]

Safety Culture and Safety Climate

Finally, (re)thinking the system of process safety requires a simultaneous view of technical and social perspectives, and research to propose frameworks and models is already ongoing in this direction. There are many challenges for systems engineers: technological, personnel, procedures, management and culture, regulatory, and conceptual.[7] A systems engineering view of risk management should address both the social and technical aspects and include different levels: work, staff, management, company, regulators and associations, and government. However, links between these levels are sometimes missing but should be emphasized so that all entities have a global view of the entire system. Also, the system is dynamic and evolves in structure and behavior over time.[57] More precisely, the human and management aspects of safety are underway to be studied through the concepts of safety culture and safety climate, with both concepts sharing the fact that they have no clear definition and no consensus on how they should be measured.

Safety culture was first introduced after the Chernobyl incident in the summary report of the postincident review meeting on the Chernobyl incident in 1986.[58] In this report, safety culture is mentioned but is not really defined. There have been many attempts to define safety culture and safety climate, but most definitions are broad and implicit, and there is no universally accepted definition. Nevertheless, Fernandez-Muniz[59] proposed the following definition for *safety culture*: a set of values, perceptions, attitudes, and patterns of behavior with regard to safety shared by members of an organization and a set of policies, practices, and procedures relating to the reduction of employees' exposure to occupational risks, implemented at every level of the organization, and reflecting a high level of concern and commitment to the prevention of incidents and illnesses.

The research on organizational climate started in the 1970s, and the term *organizational culture* was also introduced in the 1980s.[60] Despite attempts to separate these two, *organizational culture and climate,* there is some agreement that culture is the policies and goals set by an organization and climate is the manifestation of culture.[61] Many authors have suggested the elements for a positive safety culture, which include changing attitudes and behaviors, management commitment, employee involvement, promotional strategies, training, seminars and special campaigns,[62] mutual trust and credibility between management and employees, workforce empowerment and continuous monitoring, corrective actions, reviews of the system, and continual improvements to reflect safety.[63] Safety culture models before 2000[60] also concluded that a safety culture model should include the following categories: hardware/physical environment, software, people, and behavior. Including all these aspects in the model makes it based on a holistic approach rather than only focusing on the human factor of safety culture.

An integrative framework to maintain and improve safety,[64,65] which includes the environment, person, and behavior, is described in Figure 6. The environmental dimension, closely related to system safety engineering, as stated in the beginning of this article, would be managed through safety management systems and measured by audits or inspections. The data collected for 116 companies in Italy showed that the companies that adopted safety management systems demonstrated higher performances in the definition of safety and its communication to employees, the update of risk analysis, the identification of risks, the definition of the corrective actions, and employee training.[66]

The personal dimension, that is, the psychological aspects, is mostly evaluated by safety climate questionnaires, which consist of a series of questions addressing people beliefs, values, and perceptions of different aspects of safety. An example of this was demonstrated by Mearns and coworkers,[67,68] who applied the approach to 13 oil and gas companies in the North Sea over 2 consecutive years. The questionnaire was structured around topics such as their involvement, communication, and satisfaction about safety, management commitment, unsafe behaviors and incident reporting, and rules and procedures. The study found associations between certain safety climate scales and official incident statistics and also the proportion of respondents reporting an incident in the previous 12 months. It also showed a correlation between proficient safety management practices and lower official incident rates and fewer respondents reporting incidents.

With regard to the behavior dimension, Cooper[64] recommended peer observations, self-reporting measures and/or outcome measures, and an analysis of the incident history of a given organization so that safe and unsafe behaviors could be identified. An interesting study was conducted by Depasquale and Geller,[69] who viewed this from the point of view of the employees. A survey was performed on 245 employees from 20 different organizations where a behavior-based safety (BBS) process was already installed for a minimum of 1 year. The perception survey was given to each employee, with questions about interpersonal trust, impulsivity, involvement, perception of BBS training, and other

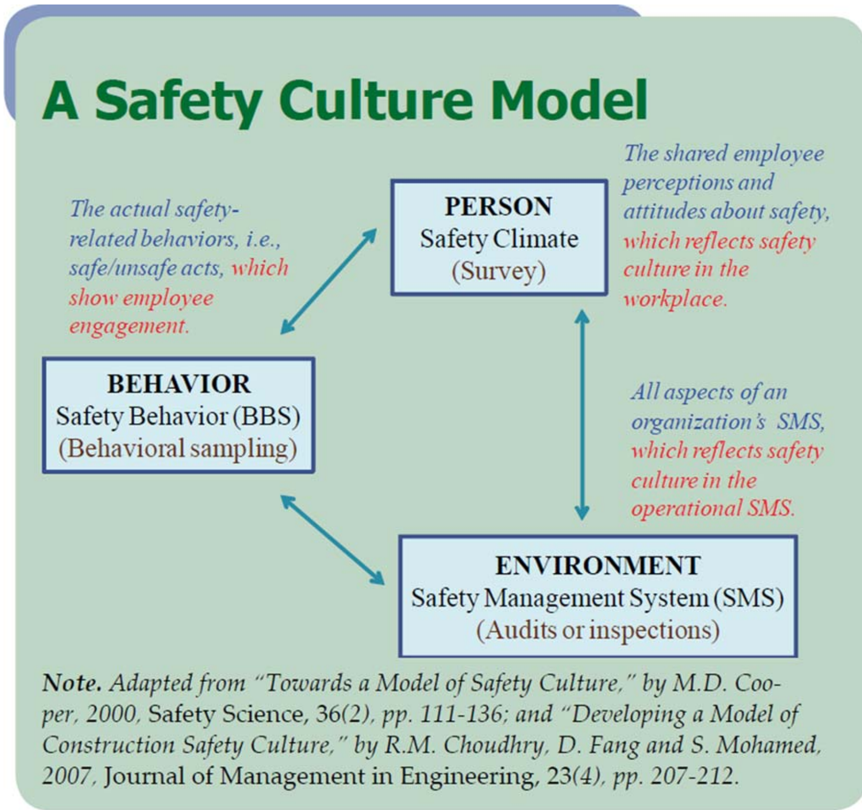

Figure 6. Safety culture model, adapted by R. Jin (2013) from Cooper.[64,65]

basic questions to see whether or not the person knew basic BBS terms, their satisfaction, and the frequency at which they used these principles. Focus group sessions were also performed. The results show that a mandatory process increased the involvement of the employees, their trust in management and coworkers, and their satisfaction with the BBS training. The mandatory process also showed a higher frequency of positive behavior-based feedback, either received or given.

From these articles, the tools and models published as measures of the safety culture are not very clear and are mostly intended to be used by managers. In addition, most of the studies or surveys have combined only two of the three dimensions.[64]

A set of criteria for safety performance evaluation methods, emphasizing their holistic approach, has been proposed;[70] it states that a safety performance evaluation method should first be supported by a theoretical framework that should establish the indicators, variables, and their logical relationships. The method should also be holistic; that is, they should integrate the technical, organizational, and human dimensions and their interrelations and intrarelations. The method should also be valid and reliable, and finally, the method should be simple and flexible and should motivate improvement. Of the six methods proposed, two of them are being implemented in the process industry: the Safety Culture Questionnaire[71] and the PyraMap[72] by Health and Safety Executive (HSE).[73] The Safety Culture Questionnaire is based on a sociotechnical model and diagnoses proactiveness, sociotechnical integration, and value consciousness with the use of a questionnaire that contains 47 elements grouped in three categories: operational safety, safety and design strategies, and personal job needs. The responses are analyzed in combination with formal audit results and communicated in a feedback meeting. The PyraMap was originally designed for Health Safety and Environmental inspectors at major hazard chemical sites with the objective of preventing major accidents (major accident prevention). Four themes were identified: (1) major accident prevention measures; (2) competence for tasks; (3) priorities, attention, and conflict resolution; and (4) safety assurance, all grouped in a pyramidal approach. The criteria developed by Sgourou et al.[70] show that methods implementing a holistic approach of safety are not yet fully developed. Some methods can work well on a small part of the problem, but more research is still needed. Knegtering and Pasman[74] stated that process safety management should focus on an adequate process safety measurement system, evaluation and analysis, a continuous learning system, and a holistic approach of control.

Recently, the concept of resilience has been applied to safety. *Resilience* is the ability of a system to respond to challenges without a loss of control.[75] A resilient system operates safely under normal, abnormal, and emergency conditions. To be resilient, a system must be proactive, interactive, reactive, and adaptive. A safety system is proactive if it anticipates incidents through systematic approaches of hazard identification and risk prioritization and reduction. It is interactive by providing information on what to do when a problem arises; reactive through preparation, planning, and training so that the organization reacts in the good way once a problem arises; and adaptive by using hands-on experience and lessons learned activities.

Another approach is the *lean safety approach,* or the application of lean manufacturing principles to safety and risk management. Originally established by Toyota,[76] a lean production is a system that uses minimal amounts of resources to produce a high volume of high-quality goods with maximum variety.[77] The book written by Hafey[78] emphasizes the importance of safety culture, demonstrates the applicability of lean tools for safety, and proposes standards and metrics. This book conveys that any lasting improvement must become both institutionalized and perpetually capable of adaptation. World class safety is not about writing correct rules but more about righting the culture responsible for the well-being of its stakeholders.

Mannan et al.[79] tried to answer the question "What are the practical attributes of best-in-class safety culture?" by identifying consensus principles harvested from a broad spectrum of organizations with exemplary safety programs. Through years of studying the underpinnings of a strong safety culture, the authors identified 10 attributes that are important in the creation of a best-in-class safety culture. The 10 attributes for the best-in-class safety culture were identified as follows: (1) leadership, (2) culture and values, (3) goals, policies, and initiatives, (4) organization and structure, (5) employee engagement and behaviors, (6) resource allocation and performance management, (7) systems, standards and processes, (8) metrics and reporting, (9) a continually learning organization, and (10) verification and audit. The analysis or evaluation of these 10 attributes for a best-in-class safety culture requires the application of system thinking on process safety and safety culture.[79] However, specific tools and methodologies still need to be clearly defined and/or validated, and more field research is needed to successfully apply system thinking and lean principles to safety.

Concluding Thoughts

Process safety is of paramount importance, and the sustainability of the chemical and energy industry is highly dependent on improved process safety performance. Sustainable development is a subject of major concern in different industry sectors. Its importance has been recognized by industry and academic communities. As a result, in the last 2 decades, sustainable-development-related content has started to appear in engineering curricula in universities worldwide. A lot of advances in terms of sustainable development regulations, engineering tools, and technology have been made. Nevertheless, industrial incidents continue to occur. The application of engineering principles to prevent further incidents and to promote sustainable development is, therefore, of paramount importance. However, the complexities and continuing changes of processing plants (commonly constituted of several subsystems that add complexity to the main system) make the application of engineering for sustainable development a challenging task and an opportunity. To accomplish the advances needed to improve process safety performance, it is imperative that we embrace innovative approaches, such as systems analysis of processes and incidents, the application of complex systems approaches, and multiscale modeling.

In this article, we have tried to show that the solution of process safety problems requires an all-inclusive approach, that is, risk assessment, LCA, the implementation of a safety culture, and various elements of engineering science. In each of these domains, we have discussed a number of important components, for example, in the section on science and engineering, we summarized the application of multiscale modeling for solving process safety problems. There is a need for more fundamental efforts to bring all of these elements together with a systems approach. Also needed is a crisp systemization that has been absent in process safety; this absence has prevented academic or/and industrial efforts from having a sustainable impact.

Literature Cited

1. US Department of Defense. *System Safety Program Requirements/Standard Practice for System Safety*. Washington, DC: US Department of Defense; 1969. MIL-STD-882.
2. Ericson CA. System safety: what, why, and how we got there. The leading edge. *NAVSEA Warfare Centers*. 2010;7:10–18.
3. Ericson CA. *Hazard Analysis Techniques for System Safety*. Hoboken, NJ: Wiley; 2005.
4. Rasmussen J, Svedung R, Svedung I. *Proactive Risk Management in a Dynamic Society*. Denmark: Swedish Rescue Services Agency; 2000.
5. Leveson NG. A new accident model for engineering safer systems. *Saf Sci*. 2004;42:237–270.
6. Leveson NG. Applying systems thinking to analyze and learn from events. *Saf Sci*. 2011;49:55–64.
7. Venkatasubramanian V. Systemic failures: challenges and opportunities in risk management in complex systems. *AIChE J*. 2011;57:2–9.
8. Bahr N. *System Safety Engineering and Risk Assessment: A Practical Approach*. Washington, DC: Taylor & Francis; 1997.
9. Hardy TL. Case studies in process safety: lesson learned from software related incidents. Paper presented at: Spring Meeting, 9th Glocal Congress on Process Safety; April 28-May 1, 2013; San Antonio, TX.
10. de Weck O, Roos D, Magee C. *Engineering Systems—Meeting Human Needs in a Complex Technological World*. Cambridge, US: MIT Press; 2011.
11. Crowl DA, Louvar JF. *Process Safety Research Agenda for the 21st Century: A Policy Document Developed by a Representation of the Global Process Safety Academia, October 21-22, 2011*. 3rd ed. College Station, US: Mary Kay O'Connor Process Safety Center; 2011.
12. Crowl DA, Louvar JF. *Chemical Process Safety: Fundamentals With Applications*. Michigan, US: Pearson College Division; 2002.
13. Mannan S. *Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control*. 4th ed. Oxford, UK: Elsevier Science & Technology; 2012.
14. Kumamoto H, Henley EJ. *Probablistic Risk Assessment and Management for Engineers and Scientists*. US: Wiley-IEEE; 2000.
15. Lapp SA, Powers GJ. Computer-aided synthesis of fault-trees. *IEEE Trans Reliability*. 1977;26:2–13.

16. Leveson NG, Stephanopoulos G. A system-theoretic, control-inspired view and approach to process safety. *AIChE J*. 2014;60:2–14.
17. Venkatasubramanian V, Rengaswamy R, Kavuri SN. A review of process fault detection and diagnosis: part II: qualitative models and search strategies. *Comput Chem Eng*. 2003;27:313–326.
18. Venkatasubramanian V, Rengaswamy R, Yin K, Kavuri SN. A review of process fault detection and diagnosis: part I: quantitative model-based methods. *Comput Chem Eng*. 2003;27:293–311.
19. US Chemical and Hazard Investigation Board. *Investigation Report, T2 Laboratories, Inc., Runaway Reaction*. Jacksonville, FL: US Chemical and Hazard Investigation Board; 2009.
20. Joseph G. Recent reactive incidents and fundamental concepts that can help prevent them. *J Hazard Mater*. 2003;104:65–73.
21. Mannan MS. The Buncefield explosion and fire—lessons learned. *Process Saf Prog*. 2011;30:138–142.
22. Paltrinieri N, Dechy N, Salzano E, Wardman M, Cozzani V. Lessons learned from Toulouse and Buncefield disasters: from risk analysis failures to the identification of atypical scenarios through a better knowledge management. *Risk Anal*. 2012;32:1404–1419.
23. Weinan E. *Principles of Multiscale Modeling*. Cambridge, United Kingdom: Cambridge University Press; 2011.
24. Ng KM, Wibowo C. Beyond process design: the emergence of a process development focus. *Korean J Chem Eng*. 2003;20:791–798.
25. Azapagic A. Life cycle assessment and its application to process selection, design and optimisation. *Chem Eng J*. 1999;73:1–21.
26. Scientific Applications International Corporation. *Life Cycle Assessment: Principals and Practice*. Cincinnati, OH: National Risk Management Research Laboratory; 2006. http://www.epa.gov/nrmrl/std/lca/lca.html. 2006. Last day accessed: September 9th 2015.
27. International Organization for Standardization. *Environmental Management—Life Cycle Assessment—Part 1: Principles and Framework*. Geneva, Switzerland: International Standards Organization; 1997. ISO/DIS 14040.
28. Fava JA, Dennison R, Jones B, et al. *A Technical Framework for Life-Cycle Assessment*. Washington, DC: Society for Environmental Toxicology and Chemistry and Society for Environmental Toxicology and Chemistry Foundation for Environmental Education; 1991.
29. Consoli F, Allen D, Boustead I, et al. *Guidelines for Life-Cycle Assessment: A "Code of Practice."* Brussels, Belgium: Society for Environmental Toxicology and Chemistry; 1993.
30. Kniel GE, Delmarco K, Petrie JG. Life cycle asssessment applied to process design: environmental and economic analysis and optimization of a nitric acid plant. *Environ Prog*. 1996;15:221–228.
31. International Organization for Standardization. *Environmental Management—Life Cycle Assessment—Part 2: Goal and Scope Definition and Life Cycle Inventory Analysis, Voting Draft*. Geneva, Switzerland: International Organization for Standardization; 1997. ISO/DIS 14041.
32. International Organization for Standardization. *Environmental Management—Life Cycle Assessment—Part 3: Life Cycle Impact Assessment, Committee Draft*. Geneva, Switzerland: International Organization for Standardization; 1998. ISO/DIS 14042.
33. International Organization for Standardization. *Environmental Management—Life Cycle Assessment—Part 4: Life Cycle Interpretation, Voting Draft*. Geneva, Switzerland: International Organization for Standardization; 1998. ISO/DIS 14043.
34. Jensen AA. *Life Cycle Assessment (LCA): A Guide to Approaches, Experiences and Information Sources*. European Communities; 1998. Available at: http://www.epa.gov/nrmrl/std/lca/pdfs/Issue20report20No206.pdf. Last day accesed September 9th 2015
35. de Haes HU, van Rooijen M. *Life Cycle Approaches—The Road from Analysis to Practice*. Paris, France: UNEP/SETAC Life Cycle Initiative; 2005.
36. International Electronic Commission. *Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems*. US: IEC 61508 International Electronic Commission; 2003. Available via http://www.iec.ch/functionalsafety/. Last day accessed: September 9th 2015.
37. Hurme M, Rahman M. Implementing inherent safety throughout process lifecycle. *J Loss Prevention Process Ind*. 2005;18:238–244.
38. Ali R. How to implement a safety life cycle. *Valve Mag*. Summer Issue 1:1–6. 2007.
39. Knegtering B. *Safety Lifecycle Management in the Process Industries*. Eindhoven, The Netherlands: Technische Universiteit Eindhoven, 2002.
40. Kidam K, Hurme M. Design as a contributor to chemical process accidents. *J Loss Prevention Process Ind*. 2012; 25:655–666.
41. Kletz TA. Inherently safer plants. *Plant/Operations Prog*. 1985;4:164–167.
42. Palaniappan C, Srinivasan R, Tan R. Selection of inherently safer process routes: a case study. *Chem Eng Process Process Intensification*. 2004;43:641–647.
43. Mannan S. Hazard identification. In: Mannan S, ed. *Lees' Loss Prevention in the Process Industries*. 3rd ed. Burlington, VT: Butterworth-Heinemann; 2005:1–79.
44. Leong C, Shariff A. Inherent safety index module (ISIM) to assess inherent safety level during preliminary design stage. *Process Safety Environ Prot*. 2008;86:113–119.
45. Rusli R, Shariff A. Qualitative assessment for inherently safer design (QAISD) at preliminary design stage. *J Loss Prevention Process Ind*. 2010;23:157–165.
46. Etowa CB, Amyotte PR, Pegg MJ, Khan FI. Quantification of inherent safety aspects of the Dow indices. *J Loss Prevention Process Ind*. 2002;15:477–487.
47. Kletz TA. What you don't have, can't leak. *Chem Ind*. 1978;4:287–292.
48. Gupta J, Hendershot D, Mannan S. The real cost of process safety—a clear case for inherent safety. *Process Saf Environ Prot*. 2003;81:406–413.
49. Srinivasan R, Natarajan S. Developments in inherent safety: a review of the progress during 2001-2011 and opportunities ahead. *Process Saf Environ Prot*. 2012;90: 389–403.

50. Edwards D, Lawrence D. Assessing the inherent safety of chemical process routes: is there a relation between plant costs and inherent safety? *Chem Eng Res Des.* 1993;71:252–258.
51. Heikkila AM. *Inherent Safety in Process Plant Design an Index-Based Approach [dissertation]*. Helsinki, Finland: Technical Research Centre of Finland, Helsinki University of Technology; 1999.
52. Srinivasan R, Nhan NT. A statistical approach for evaluating inherent benign-ness of chemical process routes in early design stages. *Process Saf and Environ Prot.* 2008; 86:163–174.
53. Bollinger RE, Crowl DA. *Inherently Safer Chemical Processes: A Life Cycle Approach*. Center for Chemical Process Safety of the American Institute of Chemical Engineers Wiley, 1997.
54. Khan F, Amyotte P. How to make inherent safety practice a reality. *Can J Chem Eng.* 2003;81(1):2–16.
55. Hansson SO. Promoting inherent safety. *Process Saf Environ Prot.* 2010;88:168–172.
56. Mary Kay O'Connor Process Safety Center. *Challenges in Implementing Inherent Safety Principles in New and Existing Chemical Processes [white paper]*. College Station, TX: Mary Kay O'Connor Process Safety Center; 2002.
57. Rasmussen J. Risk management in a dynamic society: a modelling problem. *Saf Sci.* 1997;27:183–213.
58. The International Nuclear Safety Advisory Group (INSAG). *Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident*. International Atomic Energy Agency, Vienna, 1986.
59. Fernandez-Muniz B, Montes-Peon JM, Vazquez-Ordas JC. Safety management system: development and validation of multidimensional scale. *J Loss Prevention Process Ind.* 2007;20:52–68.
60. Guldenmund FW. The nature of safety culture: a review of theory and research. *Saf Sci.* 2000;34:215–257.
61. Olive C, O'Connor TM, Mannan SM. Relationship of safety culture and process safety. *J Hazard Mater.* 2006; 130:133–140.
62. Vecchio-Sudus AM, Griffith S. Marketing strategies for enhancing safety culture. *Saf Sci.* 2004;42:601–619.
63. Choudhry RM, Fang D, Mohamed S. The nature of safety culture: a survey of the state-of-the-art. *Saf Sci.* 2007;45:993–1012.
64. Cooper MD. Towards a model of safety culture. *Saf Sci.* 2000;36:111–136.
65. Cooper MD. Safety culture, a model for understanding and quantifying a difficult concept. *Prof Saf.* 2002;June:30–36.
66. Bottani E, Monica L, Vignali G. Safety management systems: performance differences between adopters and non-adopters. *Saf Sci.* 2009;47:155–162.
67. Mearns K, Whitaker SM, Flin R. Benchmarking safety climate in hazardous environments: a longitudinal, interorganizational approach. *Risk Anal.* 2001;21:771–786.
68. Mearns K, Whitaker SM, Flin R. Safety climate, safety management practice and safety performance in offshore environments. *Saf Sci.* 2003;41:641–680.
69. DePasquale JP, Geller ES. Critical success factors for behavior-based safety: a study of twenty industry-wide applications. *J Saf Res.* 1999;30:237–249.
70. Sgourou E, Katsakiori P, Goutsos S, Manatakis E. Assessment of selected safety performance evaluation methods in regards to their conceptual, methodological and practical characteristics. *Saf Sci.* 2010;48:1019–1025.
71. Grote G, Kuenzler C. Diagnosis of safety culture in safety management audits. *Saf Sci.* 2000;34:131–150.
72. Bellamy LJ, Geyer Tim AW. *Development of a Working Model of How Human Factors Safety Management Systems and Wider Organisational Issues Fit Together*. Health and Safety Executives Research Report; 2007.
73. Dagdeviren M, Yuksel I. Developing a fuzzy analytic herarchy process (AHP) model for behavior-based safety management. *Inf Sci.* 2008;178:1717–1733.
74. Knegtering B, Pasman H. Safety of the process industries in the 21st century: a changing need of process safety management for a changing industry. *J Loss Prevention Process Ind.* 2009;22:162–168.
75. Hardy TL. Resilience: a holistic safety approach. Paper presented at: Reliability and Maintainability Symposium (RAMS), January 27-30, 2014; Colorado Springs, CO.
76. Womack J, Jones D. *The Machine that Changed the World*. New York, NY: Simon and Schuster; 1990.
77. Dennis P. *Lean Production Simplified*. New York, NY: Productivity; 2002.
78. Hafey RB. *Lean Safety: Transforming Your Safety Culture with Lean Management*. Florida, US: CRC Press; 2009.
79. Mannan MS, Mentzer R, Zhang J. Framework for creating a best-in-class safety culture. *J Loss Prevention Process Ind.* 2013;26:1423–1432.