3.12 Technological risk: chemical releases

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3.12.1 Introduction

In 1921, an explosion of 4 500 tonnes of ammonium nitrate sulphate fertiliser at a BASF site in Oppau, Germany, killed more than 500 people and caused considerable damage to the site and surrounding community. At the time, Carl Bosch, BASF's Nobel Prize-winning engineer said, 'The disaster was caused neither by carelessness nor human failure. Unknown natural factors that we are still unable to explain today have made a mockery of all our efforts. The very substance intended to provide food and life to millions of our countrymen and which we have produced and supplied for years has suddenly become a cruel enemy for reasons we are as yet unable to fathom.' This statement was no doubt true in 1921, when chemical manufacturing was still a new and growing industry. 100 years later, however, thanks to the work of generations of dedicated scientists in industry and academia, 'unknown natural factors' are rarely an underlying cause or chemical accidents today.

Accident reports, investigation results and media reports of recent times give overwhelming evidence that chemical accidents today are mainly caused by a failure to apply what is already known, the 'known knowns'. Improvements in our understanding of chemical accident risks and chemical accident control technologies and systems have not necessarily led directly to advances in a significant reduction in chemical accident disasters. Indeed, according to a famous study by H. W. Heinrich (1931), 98 % of all industrial accidents are preventable. However, technological disasters are by their nature '(hu)manmade' and it can be argued that a reduction in chemical disaster risk is particularly affected by the dependence on humans to manage and use the technology appropriately. Turner and Pidgeon (1997) argue that disasters arise from an absence of knowledge at some point. They occur because we do not understand enough about those forces (i.e. in industrial processes) that we are trying to harness, and, as a result, energy is released at the wrong time or in the wrong place. They are also clear that this is not just an engineering issue and that many disasters arise from social or administrative causes or the combination of technical and administrative causes.

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The science of reducing chemical accident risks is now focused on the underlying causes of human failure to control the risks. Characterising causality in this way adds new dimensions to the study of chemical accident risks. In attributing causality to control, there is a recognition that further progress in reducing chemical accident risks requires strong involvement of the social sciences. Certainly, there is considerable room to examine new engineering solutions, such as the use of artificial intelligence and adapting existing control technologies to new processes. However, these types of solution are industry and even process specific and do not apply to many sectors in which accidents frequently occur. Indeed, the oil and gas industry is one of the world's oldest industries and has been the subject of massive technological investment over many decades; however, globally it is by far the leader in terms of the frequency of severe chemical accidents.

The term 'hazardous industries' comprises numerous substances, processes and equipment, with considerable variation within each category in regard to properties, function and behaviour under different conditions. Petroleum refineries, bulk chemical production (e.g. chlorine and ammonia), the manufacture of specialty chemicals (e.g. paints, dyes, plastics and resins) and pharmaceuticals are examples of industries that comprise a wide range of processes, each with their own unique risk profile and associated risk management implications. While there is less variety, there is still considerable danger in processes involving hazardous substances in the 'non-chemical' industries, such as water and waste treatment, electroplating and food production. In addition, distribution activities, including transport by rail, road and pipeline, as well as explorative and extractive activities both on- and offshore, also are important sources of chemical accident risk. The evaluation of the potential for chemical accidents triggered by natural hazards (so-called Natech accidents, see Chapter 3.14) or other external events, as well as incidents caused by intentional acts, involves additional factors (e.g. natural hazard forecasting, earthquake protection, site security, etc.). These types of incident risks are not specifically addressed in this paper, but it is assumed that standard risk management practices, as here, also help to prevent and mitigate such events.

In societies with mature risk regulation, such production and use of hazardous substances is permitted provided that the risks remain at a level deemed acceptable by the local community and society in general. This paper presents evidence that industrialised countries are still far from achieving an acceptable level of chemical accident risk. It then describes a number of underlying causes common to all industries and societies that are impeding progress in chemical accident risk reduction.

3.12.2 Chemical accidents with serious impacts continue to occur with disturbing regularity

Chemical accidents are still a relatively frequent occurrence in all industrial countries and raise important questions about the adequacy of disaster risk-reduction efforts. Media monitoring over the last several years shows consistently that at least 25-30 chemical accidents with worker or community impacts are reported each month around the world in industrialised countries. Preliminary results of a study by Wood et al. (2016) of accident reports covering all major chemical hazards in fixed facilities and transport over the last 5 years (2012-16) identify 29 national and regional chemical accident disasters and 21 chemical accidents with evident high local impact.

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Disasters were classified on the basis of reported impacts on human health, the local community or the environment or on the basis of significant attention at a national level in processing and storage facilities and distribution networks (transport and pipelines). 'Local shocks' were are accidents identified on the basis of important local impacts as reported in the newspapers, corresponding to at least gravity level 3 on the European Gravity Scale for Industrial Accidents (Committee of Competent Authorities for Implementation of the Seveso Directive, 1994). In total, these accidents accounted for

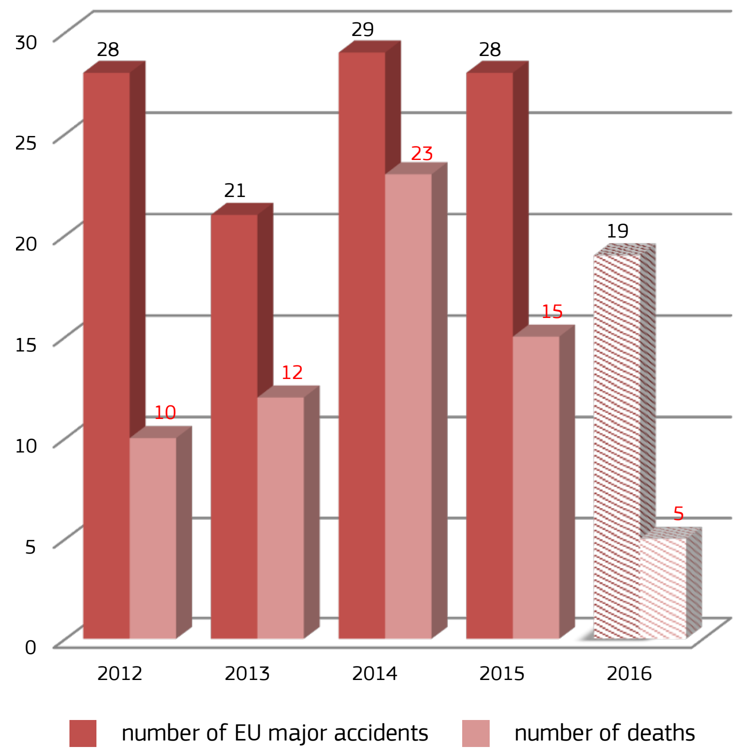
928 deaths, and (where reported) 22 973 injuries. In addition, significant environmental impacts were recorded, with one pipeline disaster reaching USD 257 million (EUR 236 million) in restoration costs (LATimes, 2017). More than 7 000 people were evacuated for several months owing to a slow leak of natural gas that was finally sealed off in February 2016 (October 2015-February 2016, Aliso Canyon, CA, USA). Insurance companies recorded nine accidents resulting in >USD 100 million (EUR 92 million) in damages, including two accidents (Hazardous goods warehouse, Tianjin, China, 12 August 2015 and petroleum refinery fire, 15 June 2014, Achinsk, Russia) costing >USD 1 billion (EUR 0.92 billion). Many other impacts, including job losses, environmental impacts, emergency response costs, damage to nearby buildings and market and production losses were sparsely reported, but businesses in West Virginia were reported to have lost USD 61 000 000 (EUR 56 000 000) in 4 days.

Belke (1998) states:

'From the perspective of the individual facility manager, catastrophic events are so rare that they may appear to be essentially impossible, and the circumstances and causes of an accident at a distant facility in a different industry sector may seem irrelevant. However, from our nationwide perspective at [U.S.] EPA and OSHA, while chemical accidents are not routine, they are a monthly or even weekly occurrence, and there is much to learn from the story behind each accident.'

FIGURE 3.54

European Commission eMARS reporting system.
Source: eMARS (2012)



The frequency of severe chemical accidents is at odds with society's expectations. Societies are becoming increasingly risk averse and failure is less readily tolerated. There are indications that the frequency of serious chemical accidents is higher than expected in many industrialised countries. In 2015 the number of deaths from major accidents on the ≈10 000 EU Seveso sites was estimated to be at least 15 (see Figure 3.54). This statistic, if confirmed, means that the frequency of one fatality on a major hazard site in the European Union was around 1.5×10^{-3}, that is, above acceptable limits for individual risk in EU Member States that use quantitative criteria. (e.g. the criteria established for individual risk (probability of 1 fatality) is $< 1 \times 10^{-6}$ in both the Netherlands and the United Kingdom, although lower probabilities may be accepted in some circumstances, for example, depending on economic costs and benefits (Ham et al., 2006)). In 2013, the President of the United States issued an Executive Order to improve chemical facility safety and security following various high-profile chemical accidents. In recent years, chemical accident frequency and severity in other major industrialised countries, such as China and Brazil, has been approaching, or has approached, levels that would be generally considered unacceptable in an industrialised economy.

Globalisation and the export of technology have increased chemical accident risk outside the EU.

Similar trends are noted in developing countries (see Figure 3.55). The terms 'developed' and 'developing' are used in this paper to differentiate countries with modern physical and institutional infrastructures from those that are still in the process of establishing such infrastructures. 'Industrialised countries' refers to both developed countries and newly industrialised countries, in which the manufacturing sector has a significant economic presence. China enacted the Emergency Event Response Law of 2007 as a result of an important lesson learned from two major chemical accidents in China: the 2003 gas well blowout in Chongqing that caused 243 deaths mainly from hydrogen sulphide inhalation, and the 2005 release of toxic substances into the Songhua River (Zhao et al., 2014). New legislation in Brazil covering chemical risks stems from broad-based concerns about problems connected with chemical safety that have grown in intensity and extent in the last two decades. Many developing 2014countries have experienced rapid growth in hazardous operations in particular segments of the oil and gas, chemical and petrochemical industries and mining, driven by a combination of factors, including increased demand in emerging economies, access to raw materials and the need to lower production costs, facilitated by a decline in trade barriers and government incentives to attract foreign investors (de Freitas et al., 2001).

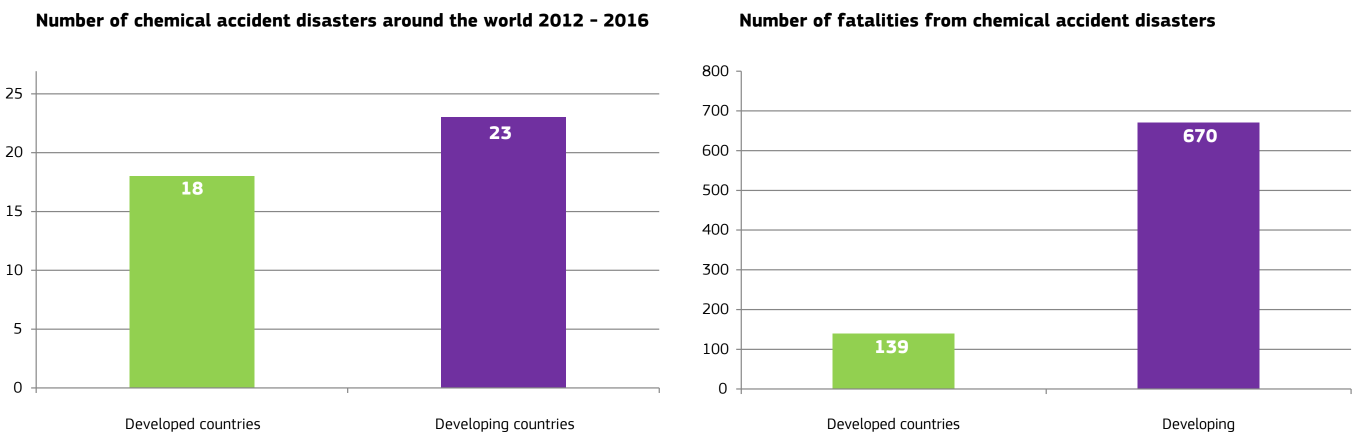
FIGURE 3.55

Chemical accident disasters reported from 2012-16 (N=29), occurring in industries producing, handling or storing dangerous substances, including oil and gas, petrochemical and chemical industries, as well as 'non-chemicals' business, such as power generation, food manufacturing and water treatment.

The frequency of chemical disasters occurring in developing countries in the period 2012-16 was more or less equivalent to that of developed countries, but fatality rates were much higher. It is speculated that risks to humans are less well-managed in developing countries.

Non-human impacts (environment, economic loss, property damage) were often quite severe in both developed and developing regions.

Source: Wood et al. (2016)



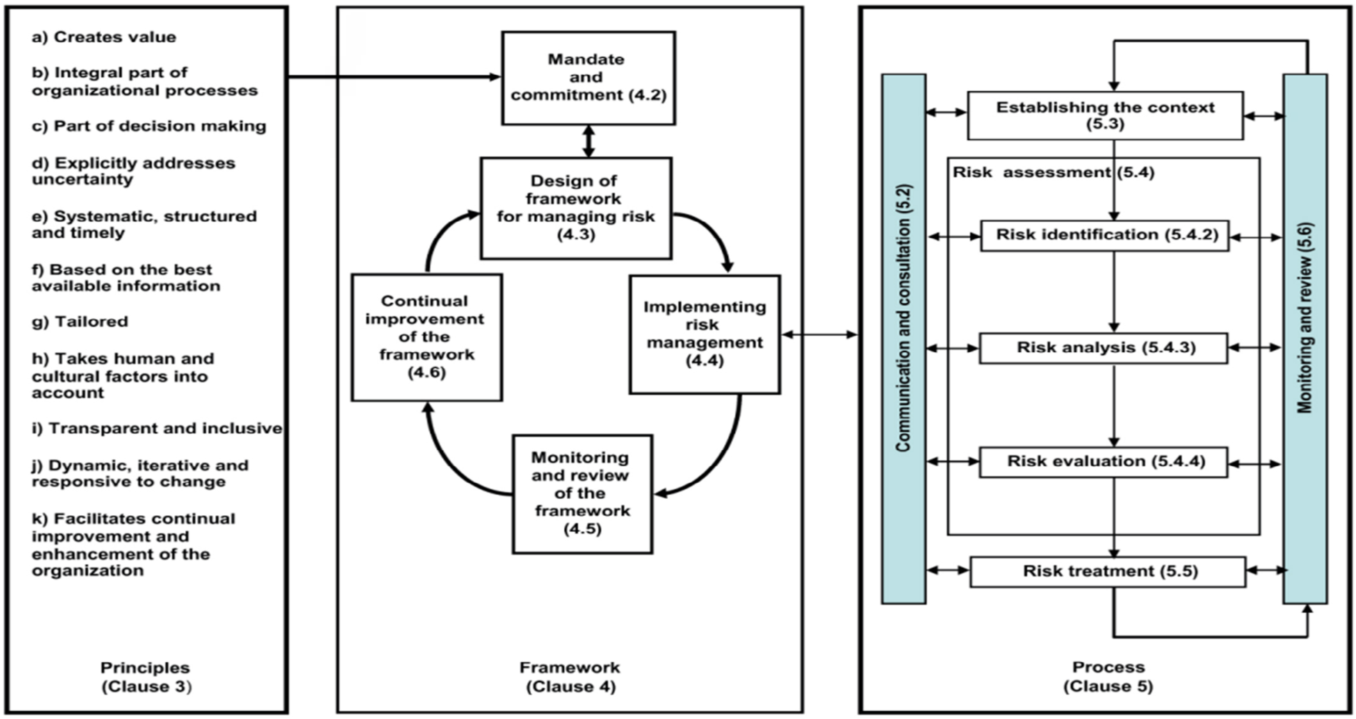
3.12.3 Chemical risk management in modern times: the theory is well-established but implementation lags behind

There is currently considerable agreement on the fundamental principles of process safety management which, if understood and properly applied, would prevent a large majority of chemical accidents that still occur today. These essential principles are then applied in the context of an ISO 31000:2009 risk management process (see Figure 3.56). From an operational perspective, successful risk management comes from applying layers of protection throughout the process life cycle (design to decommissioning), starting with the reduction of the hazard itself, and working outwards to accident prevention, mitigation and response. Above all, it is the organisations and individuals that manage all of these elements. For this reason, hazardous sites are expected to have a safety management system in place, a derivative of the well-known 'management system' concept, to manage the interface of humans with hazardous processes in order to minimise process hazard risks.

The hazardous industries understand in principle how to manage chemical accident risks. Why, then, do these industries continue to repeat failures of the past and have accidents and, sometimes, disasters? A study of accidents of the past few decades and the work of numerous experts on man-made disasters, including chemical accidents, as well as nuclear, space and aviation disasters, suggest that the causes are systemic. Sweeping changes in business philosophy and the explosion of opportunity created by new technology, such as the increasing reliance on the computerisation of business processes, have brought ben-

FIGURE 3.56

Relationship between the risk management principles, framework and processes (ISO 31000:2009 Risk management – Principles and guidelines)
Source: International Organization for Standardization (n.d.)



efits as well as a share of risks. These risks are particularly notable for man-made risks where small changes to complex systems can unwittingly remove barriers to initiation or propagation of a potential hazard event.

It is a fact that technological disasters, past and present, not just chemical disasters, have relevant and timeless lessons for risk managers in all industries, many of which have been recently documented by Gil and Atherton (2008, 2010)). A number of high-profile technological disasters occurring since 2000 have challenged some experienced risk management experts to identify the patterns underlying the repeated failures behind the latest round of technological accidents, building on the work of Perrow (1984) and Rasmussen (1975), among others, on managing risk in complex systems, by means of new approaches. Hollnagel et al. (2008) have introduced the concept of 'resilience engineering' for technologically complex industries. They look at risk management from the organisational perspective of the large multinational and government operators that are the owners and operators of these technologies. In resilient systems, individuals and organisations habitually adjust their performance to match the variability of risk over time, 'prior to or following changes and disturbances so that it can continue its functioning after a disruption or a major mishap, and in the presence of continuous stresses.' Klinke and Renn (2006) suggest that 'risks must be considered as heterogeneous phenomena that preclude standardised evaluation and handling' in their paper describing governments' potential role in managing systemic risks. Le Coze (2013) proposes that new analytical models for safety assessment take into account the dynamic and systemic aspects of safety.

Chemical accidents nowadays are often derived from the failure of industry, government and society to understand the profound effect that their choices have on risk.

Kletz (1993) commented on the pattern of corporate memory loss in United Kingdom companies as far back as 1993. More recently, Baybutt's 2016 review of accidents investigated by the U.S. Chemical Safety Board since 1998 concluded 'Remarkably, all of the reviewed incidents involved some type of deficiency or omission in adhering to established process safety practices. In many cases there were multiple deficiencies and omissions.' Wood et al. (2016) also found that where probable causes of accidents have been ascertained, they are most often associated with predictable circumstances in which control measures were insufficient as a result of poor risk management or, in some cases, a lack of adequate awareness of the risks. This finding is further substantiated in various 'lessons learned' publications, such as the MAHB Lessons Learned Bulletin, where analyses of recent and older accidents are side-by-side, identifying often remarkably similar findings about what went wrong (European Commission Joint Research Centre, 2012-2016).

The research of Taylor et al. (2016) collated and synthesised circumstances and causality associated with 12 significant technological accidents, of which five were chemical accidents, and identified numerous organisational failures associated with leadership, oversight and scrutiny, and communication that were common precursors to the events studied. Their study identified a number of factors, including the general decline of safety departments, oversimplification to upper management through aggregation of indicators and other inputs, poor understanding of operational 'reality', lack of processes and systems that ensure that process safety risks are properly assessed, and the influence of commercial interests, as among the key forces that shaped the events leading to the accidents. Arstad and Aven (2017) point out that 'it is dangerous to assume that system boundaries can be limited to the sharp end of the business … wide and open system boundaries recognise the importance of many more risk sources and safety.' They also remark on the tendency to oversimplify risks ('complexity is incompressible') associated with complex technologies. With petroleum-based industries as a primary candidate, Carnes (2011) outlines a High Reliability Governance model based on multiple engagements between government and industry actors, which continually reinforces common performance expectations and a high-level safety culture.

A large number of scientific studies of technological disasters focus on big, well-resourced organisations. However, it is a fact that many serious accidents around the world originate in small and medium-sized enterprises

(SMEs) that are operating fairly simple processes (e.g. warehouses, fuel distribution) (European Commission Joint Research Centre, 2012-2016; Gil and Atherton, 2010; Howard, 2013; State Administration of Work Safety (China), 2016; U.S. Chemical Safety Board, 2016b). While they are not all 'disasters', the United Nations Development Programme (UNDP)'s 2004 report on reducing disaster risks correctly cites that accidents with local impacts are an important part of understanding the scale and dimensions of particular threats. In addition, there is some evidence that government and society unwittingly, for sometimes for very good reasons, accept more risk in relation to SMEs. These companies often present significant challenges for regulators because they lack adequate expertise or even sufficient hazard awareness to manage their risks within acceptable limits. Typical cases of this type are the small fireworks manufacturers whose premises have been the sites of several accidents with multiple fatalities in the past 5 years within the EU (eMARS, 2012; Wood et al., 2016). Moreover, recent tragedies, such as the disasters of Tianjin, China (2015) (State Administration of Work Safety (China), 2016) and West, Texas (2013) (U.S. Chemical Safety Board, 2016b) indicate that, in these cases, even though the presence of a significant hazard was known, the government failed at many levels to ensure that adequate prevention, mitigation and preparedness measures were in place.

Twelve underlying causes are cited as challenges to controlling chemical accident disaster risk in current times.

The authors of this paper have identified 12 types of underlying causes of chemical accidents based on their own studies of accidents and research of other experts. They are based in part on causal typologies developed by the various experts in man-made risks already cited in this paper. They also reflect the authors' extensive experience in studying and investigating the causes of chemical accidents, bringing in the small business and governmental

BOX 3.3

Distant leadership and optimisation strategies: a recipe for organisational failure.

The accident at a multinational liquefied natural gas plant in South Gippsford, Australia, in 1998, known as the 'Longford accident', is attributed in part to a series of company misjudgements, including relocation of expertise to another site, poor intercompany communication and the insufficient prioritisation of safety over profits . Two people were killed and eight were injured. The state of Victoria was left without its primary gas supply, crippling industry, in particular commercial industry, with an estimated economic loss of at around AUD 1.3 billion (Hopkins, 2014). Similarly, the lack of adequate oversight of operations at a fuel storage terminal, coupled with poor intercompany communication exchange, was considered a leading cause of the devastating Buncefield explosion and fire at the Buncefield fuel terminal, Hemel Hempstead, United Kingdom, in 2005 (U.K Health and Safety Executive, Environment Agency and the Scottish Environmental Protection Agency, 2005). The primary causes were the failure of two-level instruments on the tank that overflowed. The alarm and overfill protection functions did not operate as a result. The analysis of the event indicates that it was the result of a sequence of management failures in addressing known risks and performance uncertainties over a period of months and even years prior to the incident (Howard, 2013).

dimensions that are sometimes not well covered in research.

Causes are not necessarily mutually exclusive, since the presence of one underlying cause can make a site susceptible to other dangerous mentalities and conditions. The 12 underlying causes are as follows:

1. **Lack of visibility.** A paucity of chemical accident data and inconsistent media attention has exacerbated the lack of interest in reducing chemical accident risks in recent decades. The limited public databases on chemical accidents leave society without any performance measures. With the exception of high-cost accidents reported by insurance companies, there are no published statistics on accident frequency. International media picks up only high-profile disasters, which form only a small fraction of the chemical accidents that happen every week. Moreover, as noted by Quarantelli (1997), there is also a misleading tendency to equate disastrous occasions only with casualties and property damage. Hence, there is far less visibility for chemical accidents that cause significant social disruption, such as evacuation, loss of drinking water, severe environmental damage, job loss and elevated and often uncertain exposure to health risks.

2. **Failure to manage risk across boundaries.** The organisations and individuals in charge of chemical accident risks usually define challenges in terms of their own expertise and jurisdictions. There are numerous incidents in the EU eMARS database indicating a failure to communicate information to those who need it, both internally to organisations and externally to other industrial sectors, professional disciplines and international boundaries (eMARS, 2012; European Commission Joint Research Centre, 2012-2016). Chemicals risk management in industry has traditionally been assigned to chemical and mechanical engineers who have little training in human and organisational factors. Government assigns monitoring and enforcement on the basis of who is affected, that is, onsite workers (labour authorities), offsite communities (civil protection authorities) or the environment (environmental authorities). The large multinational industries, such as oil and gas, and chemical manufacturing companies, exchange little information on chemicals risk management with other (and often less-resourced) industrial sectors, such as pyrotechnics production, pharmaceuticals and various non-chemical businesses. Similarly, government oversight and enforcement tends to follow jurisdictional boundaries in the geographic sense. This limitation can lead to

BOX 3.4

When industry and government both fail to learn lessons from past accidents.

Even major disasters are ignored and forgotten. A case in point is the massive explosion involving ammonium nitrate fertilisers that occurred in West, Texas, USA in 2013, which killed 15 people and destroyed 140 nearby homes. This incident was preceded by some well-known disastrous explosions involving ammonium nitrate fertilisers, in particular, Oppau, Germany, 1921 (>500 deaths); Texas City (Texas), USA, 1947 (581 deaths, > 3 000 injuries); and Toulouse, France, 2001 (29 deaths, > 2 500 injuries).

It appears that lessons from prior accidents about handling ammonium nitrate fertilisers had not been taken into account in either industry practices or fire protection laws (BP Refineries Independent Safety Review Panel, 2007). Furthermore, the potential off-site consequences of an ammonium nitrate explosion were ignored by the prevailing environmental regulation that had jurisdiction only over substances with toxic release potential. Emergency and land-use planning measures prior to the accident did not have any special provisions for a school, nursing home or residences in close proximity (U.S. Chemical Safety Board, 2016b).

a lack of regional coordination on chemical accident risk management and may present serious transboundary accident risks. The failure to see beyond one's own boundaries fosters a piecemeal approach to risk management and results in lost opportunities in sharing lessons learned and developing common strategies.

3. **Failure to learn lessons from past accidents and near misses.** There is substantial evidence that neither governments nor public authorities have learned sufficiently from past accidents. Taylor et al. (2015) note that that failure to learn was recurrent in organisations involved in some of the significant man-made disasters of the last 30 years in Europe and elsewhere. According to the study, barriers to learning were related to culture, the poor communication of findings and 'lost' corporate memory, a failure to investigate prior events, a narrow view of what was useful to learn and what constituted an opportunity to learn, and the silo effect, such that information on events does not cross internal organisational boundaries. An effective risk management programme incorporates the systematic study of past accidents occurring both on-site and elsewhere. Learning from one's own accidents (in one's organisation or jurisdiction) is important to diagnose specific weaknesses and trends. Learning from relevant accidents that occur on other sites and in other locations is essential to map all possible pathways that could lead to an accident. Even when problems are recognised, the failure to learn leads to inappropriate solutions. In industry there is a tendency to respond with increasing complexity, in the form of new, but not necessarily better, technology. Similarly, governments will respond with new or stricter, but not necessarily better, regulation.

4. **Social drivers, including economic trends.** Avoiding situations in which judgement is clouded by other considerations is a long-standing challenge of risk management, as evidenced by the accidents at BP Texas

BOX 3.5

Accidents that resulted from a combination of complexity and complacency

Macondo Oil Drilling Platform (Gulf of Mexico, 2010) The Macondo disaster of 20 April 2010, in the Gulf of Mexico, stemmed from the loss of control of an oil well, resulting in a blowout and the uncontrolled release of oil and gas (hydrocarbons) from the well. The accident resulted in the deaths of 11 workers and caused a massive, ongoing oil spill into the Gulf of Mexico (U.S. Chemical Safety Board, 2016a).

BP Texas City (USA, 2005). On 23 March 2005, a series of explosions occurred at the BP Texas City refinery during the restarting of a hydrocarbon isomerisation unit. Fifteen workers were killed and 180 others were injured (BP Refineries Independent Safety Review Panel, 2007).

Experts have noted that these two accidents were caused by severe organisational failures, which had remarkably similar causality, including (1) multiple system operator malfunctions during a critical period in operations, (2) required or accepted operations guidelines not being followed ('casual compliance'), (3) neglected maintenance, (4) instrumentation that either did not work properly or the data interpretation of which gave false positives, (5) inappropriate assessment and management of operations risks, (6) multiple operations conducted at critical times with unanticipated interactions, (7) inadequate communication between members of the operations groups, (8) a lack of awareness of risks, (9) diversion of attention at critical times, (10) a culture with incentives that provided increases in productivity without commensurate increases in protection, (11) inappropriate cost and corner cutting, (12) lack of appropriate selection and training of personnel, and (13) improper management of change (Carnes, 2011).

City (BP Refineries Independent Safety Review Panel, 2007) and the explosion and fire at the Macondo offshore drilling platform (U.S. Chemical Safety Board, 2016a). Both good and bad intentions can interfere with good risk decisions. For example, employees will tolerate bad conditions because they need jobs. Similarly, well-intentioned operators may delay maintenance and repairs on ageing sites to keep costs down and prevent the site from closing. Risk management efforts of some organisations and individuals can also by limited by systemic constraints, including a lack of political will and corruption, affecting both developed and developing countries. Economic and civil instability and a combination of long-standing cultural and structural deficiencies are a particular concern in developing countries. Economic pressure is a particular social driver that can put gains in chemical process safety at risk, particularly in the modern world when business circumstances change at a rapid pace. Instability in management and in business continuity has a knock-on effect on all aspects of risk management. In some situations, poor profit margins impose difficult decisions on various operations in terms of defining safety priorities when resources are stretched. However, there are also various trends in profitable companies, such as optimisation (operational efficiency) and the drive towards increasing shareholder value, that can undermine risk management when they are applied without due consideration of the impacts on risks.

5. **Increasing complexity.** Nowadays, change occurs more and more rapidly in all aspects of daily life. While individually the risks of technologies and associated hazards are generally known, the impacts of multiple and rapid changes in the way humans behave around them are difficult to assess and can to some extent constitute 'unknown unknowns'. As noted by Arstad and Aven (2017) for the Columbia Space Shuttle disaster, 'Always under pressure to accommodate tight launch schedules and budget cuts … certain problems became seen as maintenance issues rather than flight safety risks.' This situation is echoed in a number of the highly visible chemical accident disasters over the last few decades (e.g. BP Texas City (BP Refineries Independent Safety Review Panel, 2007), Buncefield (Howard, 2013), Macondo (U.S. Chemical Safety Board, 2016a)). Risks are not perceived as risk but rather as problems to work around. The prevailing trends are quickly replaced by new trends and existing technologies are quickly replaced by new technologies. Sites change ownership with considerable frequency (Kamakura, 2006), which is often accompanied by significant changes in management policies, work patterns, safety culture or other structures that guide norms of behaviour, and also contributes to an increasing decline in the corporate memory of accident risks (OECD, 2016). In reality, change occurs faster than the knowledge to understand how the change is affecting different aspects of our lives, including habits of living and working,

BOX 3.6

What can happen when governments are complacent.

The disastrous fire and explosion in the port of Tianjin, China, in 2015, is mainly attributed to lax safety procedures and a deliberate lack of government oversight. The owners of the storage and distribution company at the source of the accident somehow managed to persuade numerous authorities to look the other way with regard to permitting inspections and hazard control measures. The site began operations in 2014, handling and storing a variety of dangerous substances, many in volumes much higher than would be considered safe. According to the official investigation report, there was neither evidence that recognised safety standards were applied nor evidence that workers had been trained in handling hazardous goods. In addition to causing 165 deaths and injuries to nearly 800 people, 30 000 people in the surrounding community were evacuated (State Administration of Work Safety (China), 2016).

but also political, commercial and economic dimensions. As noted by Ruifeng et al. (2012), process controls and safeguarding equipment are more complex, thereby increasing newer risk that is often unforeseen. Both Mannan (2005) and Quarantelli (1997) also indicate that a correlation exists between the scale and complexity of process plants and major incidents. However, these and other modern trends are having significant consequences on safety and security, the long-term impacts of which are still not fully understood. Deeper understanding requires a multidisciplinary approach, despite the fact that the job market is exhibiting a tendency for increasing specialisation.

6. **Automation and information technology dependencies.** Twenty years ago, Quarantelli (1997) predicted that technological advances would reduce some hazards but make some old threats more dangerous, and cited computer technology as a kind of technology that represented a distinctly new danger. Indeed, the automation of activities traditionally performed by humans is a frequent adaptation of computer technology but it could in many circumstances create new risks in operations using dangerous chemicals. As pointed out by Lagadec and Topper (2012), society itself is still not clear about the full range of impacts of this innovation or other such 21st phenomena as the internet, the media explosion, social networking and smartphones. Moreover, as Taylor et al. (2016) suggest, an emphasis on interconnectivity and interdependence has become increasingly important, but when a failure occurs in one of the interconnected systems it can lead to major disruption. A further concern has emerged with the vulnerability of information technology systems to hacking or, even more simply, unforeseen potential for errors in the design and operation of automated systems that are increasingly interdependent across sites and accessed and operated by multiple users.

7. **Failure of risk management and risk assessment.** The EU eMARS (2012) and the U.S. Chemical Safety Board (2016a, b), for example, have produced many reports of recent past accidents for which the likelihood of the event occurring or the severity of its impacts could have been reduced with the application of actions within the hierarchy of risk management controls. Many of these reports also indicate a failure in the risk assessment process (e.g. that a risk assessment was not conducted, certain factors were discounted, lessons learned from previous events was ignored or that the risk associated with a change in operations was not considered). Indeed, many accidents also have been known to occur because of lack of follow-up after the monitoring and review of the functionality of the safety management system, such that the risk assessment was not updated after deficiencies in the risk assessment were discovered. Both organisations and individuals can fail to apply risk management principles, even when well established and part of training requirements. There is also often a lack of attention paid to inherent safety in which processes are designed without considering opportunities for risk reduction (chemical substitution, limiting volumes, exposure, etc.). This failure is sometimes attributed to various business and organisational trends cited in this paper, such as business climate and economic trends, organisational change and staff reductions, complexity and, sometimes, a loss of focus (complacency or 'organizational drift' (Taylor et al., 2015)); however, in other industries, particularly non-chemicals businesses and small companies, other factors, such as lack of awareness and education, are stronger influences.

8. **Corporate disconnect from risk management.** The globalisation of hazardous industries has increased both the physical and mental distance between headquarters and the sites they manage. Headquarters staff lose a tacit understanding of how sites experience chemical accident risks. For example, multinational sites can pose particular complexity when the culture and policy of the management is vastly different from that to which the site has been accustomed, especially if it is in a different country (European Commission Joint Research Centre, 2014). Corporate leaders also tend to oversimplify production safety risks (or risks are oversimplified for them) (Arstad and Aven, 2017; Taylor et al., 2015). It is assumed that new communication and automation technologies have universally positive trickledown benefits for all operations. For chemical accident hazards, the opposite is often the case. In particular, the trend towards short-term resource optimisation continues to have disturbing implications for chemical risk management. The tendency to outsource expertise and maintenance operations has already received considerable attention. There is also a preference in some companies to distribute limited expertise across many sites, so that access to critical safety expertise is

proportionately less available to sites. This phenomenon has been considered a significant factor in the Longford accident (Hopkins, 2014) as well as the catastrophic fire that occurred at the Buncefield storage site in 2005 (Howard, 2013).

9. **Insufficient risk communication and awareness.** Hazardous industries are introduced in locations with little attempt to communication and build awareness of the risks, to foster meaningful preparedness and planning, or to ensure that training and expertise are adequate for the responsibilities associated with the risk. This situation is particularly acute in developing countries where the desire for economic growth outweighs other decision factors. In many cases, risks are not so much accepted as ignored, encouraged by a historical lack of transparency in the political classes or society as a whole. When considered in context, the risk of fatal major accidents is also relatively small compared with the risks of poverty, disease and road traffic accidents and, therefore, may not receive the attention it deserves as a risk that is readily mitigated. The Enschede (the Netherlands) fireworks accident of 2000 (The Oosting Commission, 2001) and the accident in West, Texas (USA) (U.S. Chemical Safety Board, 2016b) are notable examples of how a lack of appropriate risk communication and awareness can contribute significantly to disasters.

10. **Resource and infrastructure deficiencies.** Many sites are compelled by a combination of circumstances and poor decisions to operate with less than adequate resources and infrastructure. In particular in developed countries, the physical infrastructures that underpin both public and private services are reaching the end of their normal lifespan (Quarantelli, 1997). A lack of resources generally leads to insufficient competence to manage risks (e.g. no chemical or mechanical engineer on site) or to improve degraded equipment or to apply safety management systems with rigor. Physical infrastructure can also be degraded by age or neglect, the latter of which was a key factor contributing to the catastrophic explosion and fire at the petroleum oil refinery at BP Texas City in 2005 (BP Refineries Independent Safety Review Panel, 2007). In many developing countries, it is common to start operations under less than ideal circumstances. The existing physical infrastructure may be degraded from years of neglect. There may be gaps in the education and risk awareness of local worker populations, as well as a limited availability of university-educated staff. Industries in developed countries also may suffer competency deficiencies due to declines in engineering students seeking career paths in traditional chemical process industries. Moreover, higher education in relevant engineering disciplines still excludes knowledge of chemical accident phenomena or basic principles of risk management.

11. **Deficiencies of the legal infrastructure.** In much of government and industry globally, management of chemical accident risks is focused on emergency preparedness, and strategies aimed at prevention and mitigation are not prioritised. Society as a whole exhibits a high risk tolerance owing to historically poor living and working conditions that consequently predisposes workers to accept and ignore workplace hazards. In many developing countries, there may be no legal framework to require and enforce minimum standards for process safety performance on chemical hazard sites. When a proper legal framework exists, regulators and operators lack the competence and resources to understand or enforce it. These circumstances have implications for developed countries in that companies may have sites in developing countries and their citizens may be customers of their products. However, even in developed countries, there is also a recognised pattern that governments do not often proactively engage in managing chemical accident risks until after a serious accident, or a number of serious accidents, occur. Notably, attention to chemical process safety in Australia gained widespread attention only after the Longford accident in 1998 (Hopkins, 2014), and in New Zealand following the mining accident in 2010 (Royal Commission on the Pike River Coal Mine Tragedy, 2012).

12. **Complacency in government and industry.** The longevity of chemical accident prevention and preparedness regimes in developed countries also leads many politicians and industry leaders to reduce their attention to chemical accident risks, threatening to undermine decades of risk-reduction progress. Sometimes called 'organizational drift' (Taylor et al., 2015), this phenomenon may occur in once-strong organisations and societies that allow their standards to erode over time without noticing their own decline. The perception that chemical accidents are no longer a threat eventually results in dramatic decreases in resources for enforce-

ment and risk management. Notably, there has been a dramatic lack of focus in modern times on process safety as an inherent operating requirement (not just because the legislation requires it). Government complacency can be manifested by lax application of permitting laws, reduced frequency of inspections and insufficient attention to land use and emergency planning. Complacency in industry is often evidenced by greater tolerance of deviations from accepted norms, such as process parameters, safety procedures and maintenance requirements. In developing countries, the problem is arguably worse. The vast majority of owners and operators of hazardous sites, even in large state-owned or multinational subsidiaries, are used to minimal management of chemical hazards on their sites.

3.12.4 Implications for future scientific study

The main topics that emerge as areas for further study and experimentation are listed and described below. Many are already the subject of projects in research institutes and collaborations within the international community.

Experts in all areas should work together on initiatives that promote good risk governance, creating a new paradigm for all society.

However, it is widely recognised that these problems, having proved so resistant to solutions, will require considerable reflection and patience to identify approaches that produce tangible improvements.

Experts in all areas should work together on initiatives that promote good risk governance, creating a new paradigm for all society through the following:

- Motivating corporate and government leadership. New models for the governance of hazardous industries should be explored and tested. These models should apply to corporate leadership and government alike, applying management philosophies supported by rigorous enforcement proportionate to the level and complexity of the risk. New strategies should be based on a mutual expectation between government and industry of overall corporate responsibility for maintaining risk resilience that goes far beyond the current compliance-based paradigm. Enforcement will need new (more evolved) strategies (e.g. nudge, push, force) to drive industrial practice. Concepts such as recovering the profits of illegal/unsafe activity to remove the economic advantage may also be a step forwards. Fears that the process industries could potentially have parallels to the banking crises (2008 onwards) in terms of poorly understood risks have triggered the development of the Organisation for Economic Co-operation and Development (OECD) publication Corporate Governance for Process Safety — Guidance for Senior Leaders in High Hazard Industries, an important new tool for industry and government addressing this topic (OECD, 2012).

- Systematic accident reporting, data collection and exchange. There needs to be a concentrated effort to build national and international chemical accident registers and to promote accident exchange between industries and countries. The availability of reliable chemical accident statistics will allow academics, politicians and the media to understand the magnitude and nature of chemical accident risks and identify appropriate risk-reduction measures.

- Promoting positive safety culture both industry-wide and in society. The chemical processing industries should focus serious attention on developing a positive safety culture industry-wide, such that it is resilient in the face of change, particularly in the economy and site management. Psychologists should work with industry and governments to foster risk awareness and sensitivity among citizens. An informed safety-sensitive society can help to support a broader mandate to insist that companies exercise greater corporate responsibility for reducing the risks associated with their operations.

- Heightened commitment to the Plan–Do–Act cycle in chemical process safety management. After an accident has occurred, a common finding is that a potential risk factor had been identified and ignored. In keeping with improved safety culture, guidance and training on safety management policy and performance indicators need to put more emphasis on incorporating lessons learned from past events and audit findings on deficiencies in risk management into process hazard assessments and the safety management system as quickly as possible.

- Risk management in SMEs in the chemical business. There are subcategories of SMEs in the chemical business, each of which has elevated risk for different reasons. The most challenging intellectually are the SMEs that know their risks and take care to manage them but still have accidents. More research is needed on why accidents occur in SMEs, including geographic and economic differences that may influence these risks, and on strategies to reduce them.

- Risk management in non-chemical businesses. Similarly to SMEs, studies to develop strategies and guidance to support risk management in many of these industries are still needed. There are a number of examples of this work, such as the U.S. Environmental Protection Agency's Supplemental Risk Management Program Guidance for Ammonia Refrigeration Facilities. More analysis and dissemination of lessons learned from accidents in such locations is also needed.

- Business-sector risk-reduction initiatives on a global scale. Oil and gas, extractive industries, industrial parks and large-scale chemical production should be the focus of a global collaborative effort between industry, government and aid organisations to reduce chemical accidents in these industries.

- Risk assessment models that address new technologies and complexity. Some researchers (e.g. Taylor et al., 2015; Travers, 2016) are already proposing models by which to assess risks associated with complexity. These models need to be tested and developed further. In addition, research is required to characterise and quantify various emerging risks, including those associated with the increasing use of automation and the outsourcing of critical safety functions, ownership change, how culture and competence profiles in different countries can affect chemical accident risk and other emerging concerns mentioned in this paper.

More work is needed on how business practices must change to mitigate the most common violations of safety management principles.

More work is needed on how business practices must change to mitigate the most common violations of safety management principles, in particular in relation to:

- Mechanical integrity. All too often, maintenance and repairs of equipment and infrastructure are considered dispensable when inconvenient for profit or production goals. The underlying causes should be studied and new approaches adopted that provide stronger motivation, including risk assessment requirements and government-operator interfaces (e.g. permits, inspections), for reinforcing mechanical integrity as an operating requirement.

- Management of change. This safety principle is particularly challenging because time pressures and a human preference for expediency undermine its consistent implementation. Finding methods that help companies and individuals to recognise change when a change can elevate risk is an important part of resilience engineering and a significant aspect of the 'resonance' factor described by Leonhardt et al. (2009). Resonance is a quality that explains how disproportionately large consequences can arise from seemingly small variations in performance and conditions.

- Learning lessons from accidents and failures. Industries and sites need to learn from, and remember, past accidents. Corporate memory loss, across-industry, is not an appropriate excuse. A greater investment is needed in projects to develop strategies to learn and remember, with a particular emphasis on collaborations between industry, government and academia. According to Patterson (2009), both industry and government struggle with barriers that tend to undermine systematic extraction and communication and lessons learned and there needs to be a renewed effort to overcome these barriers. As noted by Hailwood (2016), companies operating major hazard facilities should establish systems that not only ensure reporting and learning from their own accidents and near misses, but also make use of databases and reports from the accidents of others. Each country should also make resources available to investigate accident causes and lessons learned, as well as to collect and document this knowledge and make it accessible to third parties.

Renewed effort is needed to ensure that there is adequate competence in our industries and our governments for addressing chemical accident risks now and over the long term.

Renewed effort is needed to ensure that there is adequate competence in our industries and our governments for addressing chemical accident risks now and over the long term, enabled by:

- Greater access to risk management knowledge and tools. Risk management is always specific to a site. Few sites have exactly the same risks, even if they produce the same products, since the physical characteristics of the location, structures and equipment are important elements of the risk. Considerable future mechanisms are needed to ensure good management practice for all kinds of operations and to make equipment available in an easy to read format, taking account of the many different languages in which they might be needed.

- Access to risk assessment competence. Both operators of hazardous sites and regulators need to know the type and severity of accidents that could occur and have a realistic understanding of the control measures needed to ensure that the risk of such accidents is minimised. Cheap and easy access to interactive consequence assessment, risk mapping and quantitative assessment tools is urgently needed in all areas of the world.

- Strategies to combat a labour market deficient in appropriate expertise. Industry and academia need to continue to push for standardised process safety curriculums associated with chemical engineering and chemistry in particular, as well as with environmental management and other related disciplines to some extent. Multinational companies operating in developing countries need to be aware that competence and experience in risk management may be far less available than in Europe or the United States, and process operations need to be adjusted accordingly (Zhao et al., 2014). In all parts of the world, industry and the professional engineering community should do far more to support occupational and process safety education and training to produce more qualified professionals capable of identifying and managing risks in design and daily operations.

European Union industry and government must share responsibility for reducing chemical accident risks in developing countries.

European Union industry and government must share responsibility for reducing chemical accident risks in developing countries, and special emphasis should be placed on the following:

- Building basic awareness of chemical risks and how to manage them to developing countries. Basic training in chemical risks and safe chemicals management is badly needed. The remarkable efforts of numerous international organisations such as UNEP, UNECE (United Nations Economic Commission for Europe), UNEP-OCHA and the WHO, among others, are underfunded and far too fragmented to have significant impacts, despite smart management and promising results from recent initiatives. Meaningful progress is possible only with substantial commitments involving UNDP, United Nations Institute for Training and Research, the World Bank and the European Commission as well as Regional Economic Commissions in the context of a coordinated and comprehensive long-term strategy.

- Resilience and risk awareness building. There has been considerable success with stakeholder involvement approaches such as UNEP APELL to manage risks at a local level within a systemic national and international regional strategy. A number of tools, including those produced by the OECD (2003) and UNEP (2010), already exist to guide developing countries on how to build a comprehensive and effective chemical accident risk prevention and preparedness programme. The clear next step is to identify and deploy mechanisms by which to provide significant and sustained support to countries that are ready to take steps towards establishing such programmes.

- Fostering regional and international networks and collaborations on chemical accident risk management. A critical mass of policy and technical initiatives at both regional and international level, creating a constant pressure and giving developing countries easy access to expertise and technical support, is a way to establish a new norm. A number of international organisations (e.g. UNECE, 2014)) have reported increasing success with such approaches but they are barely implemented for chemical accident prevention programmes in regions such as Asia and Africa.

- Improving performance measures for interventions. Fund administrators generally lack objective measures by which to evaluate suitable candidates for chemical accident prevention programmes that may target the specific needs of and provide continued support to achieve meaningful results. Further refinement and testing of capacity-building performance indicators, and methods for qualitative assessment (e.g. level of political will, key drivers of change) such as those currently in development by the JRC (Baranzini et al., in progress), can lead to better targeting of such initiatives. These could also be useful for developed countries.

3.12.5 Conclusions and key messages

Recent accident trends provide evidence that the world is nowhere near reducing the risk of industrial accidents to acceptable levels. While developed countries have shown marked improvements, particularly in reducing the average number of fatalities associated with chemical accidents, the overall rate of major accidents with other serious impacts remains high. Throughout the world, accidents continue to stem from violations of well-known safety management principles. Such failures can only sometimes be explained by complexity and a misfortunate combinations of events; very often they may be due, entirely or in part, to incompetence, a lack of awareness or outright negligence. Many experts are exasperated that management practices and attitudes are so vulnerable to other influences and resist improvement.

In conclusion, accepted norms of industry, government and society are undermining good risk management. This finding has a number of important implications for the direction of future research, policy development and the role of government and industry in reducing accident risks.

Partnership

The findings confirm overwhelmingly that the traditional approach in which stakeholders stick to their traditional rules is not going to fix the problems in question. It is no longer possible that industry works alone to define and implement good risk management practice. Policymakers can no longer simply set performance standards and then step aside. Observations from academics, particularly in the social sciences, need to find their way into both industry and government approaches to chemical accident risk.

Knowledge

The control of chemical accident risk is very often undermined by the cultural norms and expectations associated with how government and business are expected to act, and a lack of knowledge and awareness about chemical accident risks in society in general. Combatting these forces requires new thinking about how our businesses and governments are working with these risks. As such, the essence of the change is that all society must recognise part ownership of chemical accident risk, and ownership implies both a certain responsibility for, and power to prevent, such risk. This finding in turn requires that the new approach to controlling chemical accident risks is to change culture with education and awareness.

Innovation

The recommendations in this paper suggest a paradigm change in the way the EU and the developed world in general approach chemical accident risk. Solutions must encompass a broader vision of risk ownership and boundaries of influence, recognising that the role of industry does not end beyond the fence line, that offsite forces can influence onsite risks and that society's responsibility may need to extend beyond traditional geographic boundaries. If the system is the problem, the solutions lie in changing the system.

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