3. UNDERSTANDING DISASTER RISK 2: HAZARD RELATED ISSUES

3.12. TECHNOLOGICAL RISKS: CHEMICAL ACCIDENTS

Coordinating Lead author: Elisabeth Krausmann

European Commission, Joint Research Centre, Italy, elisabeth.krausmann@jrc.ec.europa.eu

Lead Author: Maureen Heraty Wood

European Commission, Joint Research Centre, Italy, maureen.wood@jrc.ec.europa.eu

Contributing Authors:

Mark Hailwood

LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Germany

Lee Allford

European Process Safety Centre, United Kingdom

Zsuzsanna Gyenes

European Commission, Joint Research Centre, Italy, zsuzsanna.gyenes@jrc.ec.europa.eu

ABSTRACT

Chemical accident disasters are unplanned events involving hazardous substances, causing harm to human health, the environment, or economic loss or social disruption. While there is a long history of chemical accidents, with events recorded even more than 100 years ago, the study and implementation of technologies and approaches to preventing, preparing and responding to chemical accidents, only gained widespread attention in the last 40 years. There have been significant advancements in understanding accident phenomena, and in development of technology and management systems to control risks.

Nonetheless, beyond a certain level of prevention, meaningful gains in prevention seem to elude our grasp. Indeed, in developed countries, such as European Union (EU) Member States and the USA, that have by far the most sophisticated understanding and oversight of chemical accident prevention, there are still a high frequency of serious chemical accidents each year, resulting in severe human, environmental and economic consequences. Moreover, there is an increasing presence of hazardous industries and of volumes of hazardous substances in commercial use in many developing countries where experience with industrial processing hazards and risks is relatively recent and where social and political infrastructures for dealing with the plethora of externalities accompanying industrial production are inadequate.

Most experts do not believe that chemical accidents occur today because our understanding of engineering possibilities runs ahead of our understanding and predictive powers regarding their downsides. Rather, our challenges today stem from a myriad of inputs whose influence on chemical process risks is broadly known and understood, but that go largely unrecognized and unmanaged in organizations and on sites where the risks are actually present. Hence, it is not our lack of knowledge and understanding of how the technology works, but in many cases a lack of access to such knowledge, and in other cases, a failure to prioritize and use it wisely to prevent serious loss.

Chemical accidents will continue to happen in the foreseeable future as long as chemicals and chemical processing are important for society. In particular, the usage and applications of chemicals is spreading and not decreasing. Moreover, production, transport and storage of dangerous substances are happening in places where these risks were never a problem before. In the meantime, there is evidence from the repetition of accidents from previous generations within industrialized economies that lessons of the past have been forgotten or ignored. This paper outlines the trends that threaten to increase chemical accident risks and proposes some recommendations to address them.

KEYWORDS

Chemical accident prevention, Seveso Directive, chemical disaster, process safety, safety culture, economic trends, capacity building, developing countries, multinationals, learning from accidents, knowledge transfer, chemical risk management

Introduction

In 1921 an explosion of 4,500 tonnes of ammonium nitrate sulfate fertilizer at a BASF site in Oppau, Germany, killed over 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, 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.

[*] https://www.basf.com/en/company/about-us/history/1902-1924.html

Accident reports, investigation results, and media reports of recent times give overwhelming evidence that chemical accidents today are mainly caused by 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 lead directly to advances in a significant reduction in chemical accident disasters.** Indeed, according to a famous study by H.W. Heinrich, 98% of all industrial accidents are preventable. [17] However, technological disasters are by their nature “(hu)manmade” and it can be argued that reduction of chemical disaster risk is particularly affected by the dependence on humans to manage and use the technology appropriately. Turner and Pidgeon [46] 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, which we are trying to harness, and as a result energy is released at the wrong time or at 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.

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 for examining 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, and yet globally it is by far the leader in terms of frequency of severe chemical accidents.

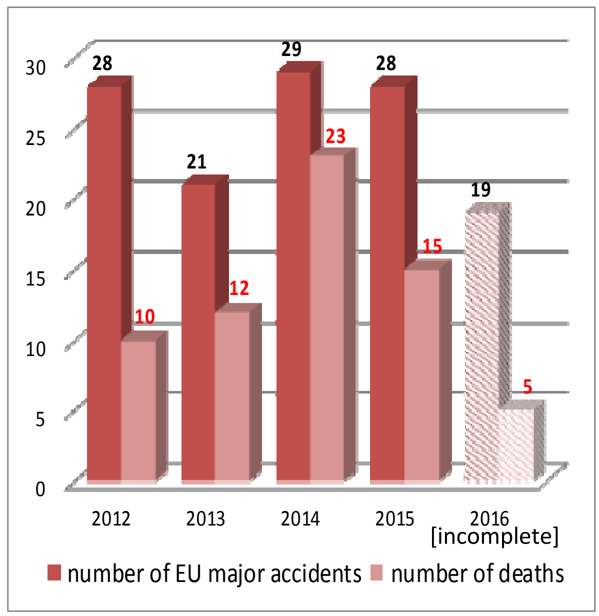
The term “hazardous industries” comprises numerous substances, processes and equipment, with considerable variation within each category in regard to properties, function, and behavior under different conditions. Petroleum refineries, bulk chemical production (e.g. chlorine and ammonia), manufacture of specialty chemicals (e.g., paints, dyes, plastics and resins), 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, on and offshore also are important sources of chemical accident risk. †

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 will give evidence that industrialized countries are still far from achieving an acceptable level of chemical accident risk. It will then describe a number of underlying causes common to all industries and societies that are impeding progress in chemical accident risk reduction.

† **The evaluation of potential for chemical accidents triggered by natural hazards (so-called Natech accidents), 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. Natech hazards are the subject of another State of the Science report.**

3.14.1 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 industrialized countries. **Error! Reference source not found.** Preliminary results of a study by Wood et al. [53] of accident reports covering all major chemical hazards in fixed facilities and transport over the last 5 years (2012-2016) identifies 29 national and regional chemical accident disasters and 21 chemical accidents with evident high local impact‡. 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 in restoration costs§. Over 7000 people were evacuated for several months due to a slow leak of natural gas that was finally sealed off in February 2016**. Insurance companies recorded 9 accidents with > USD $100 million in damages, including 2 accidents†† costing >$1 billion. Many other impacts including job loss, environmental impacts, emergency response costs, damage to nearby buildings, market and production losses were sparsely reported, but West Virginia businesses were reported to have lost $USD 61,000,000 in 4 days.



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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 national level in processing and storage facilities and distribution networks (transport and pipelines). . "Local shocks" were 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. [7]**

§ Refugio pipeline oil spill, Santa Barbara, California, USA, 19 May 2015. http://www.latimes.com/local/lanow/la-me-ln-refugio-oil-spill-projected-company-says-20150805-story.html

**** October 2015 – February 2016, Aliso Canyon, California, USA.**

†† Hazardous goods warehouse, Tianjin, China, 12 August 2015 and petroleum refinery fire, 15 June, 2014, Achinsk, Russia.

> "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." [4]

Frequency of severe chemical accidents is at odds with society's expectations

Society is 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 industrialized countries. In 2015 the number of deaths from major accidents on the ~10,000 EU Seveso sites is already estimated to be at least 15 (see Figure 1). This statistic, if confirmed, means that the frequency of 1 fatality on a major hazard site in the European Union was around 1.5 X 10-3 that is above acceptable limits for individual risk in EU Member States that use quantitative criteria. (e.g., the United Kingdom, the Netherlands)[‡‡]. 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 other major industrialized countries, such as China and Brazil, in recent years that chemical accident frequency and severity is approaching, or has approached levels which would be generally considered unacceptable in an industrialized economy.

Globalization and export of technology has increased chemical accident risk outside the EU

Similar trends are noted in developing countries (See Figure 2)[§§]. 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 blow out in Chongqing that caused 243 deaths mainly from hydrogen sulfide inhalation, and the 2005 release of toxic substances into the Songhua River. [55] 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 countries have experienced rapid growth in hazardous operations from growth in particular segments of 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.[8]

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‡‡ For example, the criteria established for individual risk (probability of 1 fatality) is < 1*10-6 in both the Netherlands and the United Kingdom, although lower probabilities may be accepted in some circumstances (e.g., depending on economic costs and benefits) [16]

§§ The terms "developed" and "developing" are used in this paper to differentiate countries with modern physical and institutional infrastructures versus those who are still in the process of establishing such infrastructures. "Industrialized countries" refers to both developed countries and newly industrialized countries, in which the manufacturing sector has a significant economic presence.

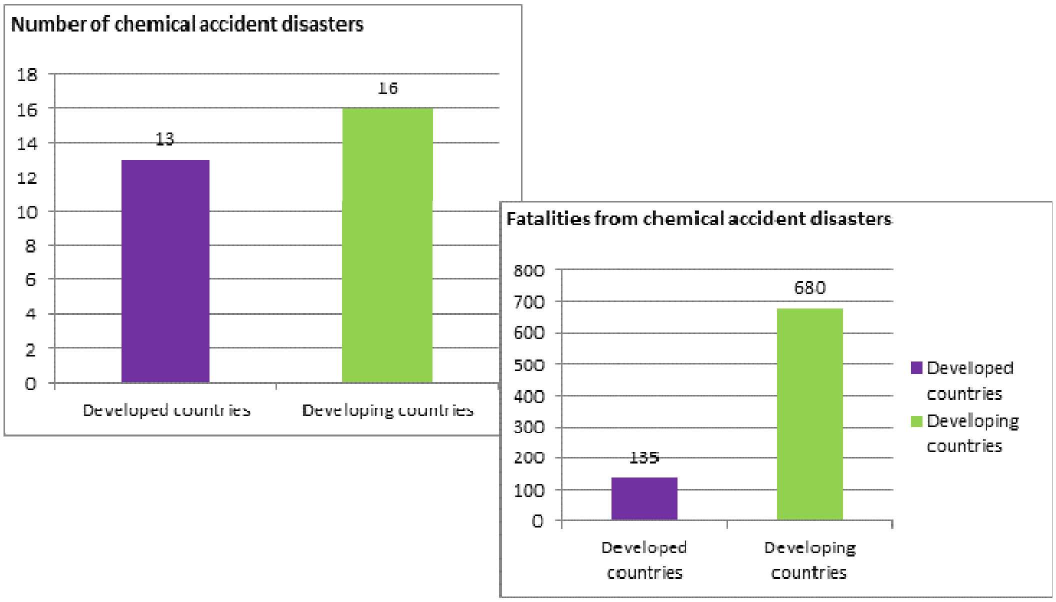

Figure 2: Chemical accident disasters reported from 2012-2016 (N=29), occurring in industries producing, handling or storing dangerous substances, including oil and gas, petrochemical and chemical industries, as well as "non-chemicals" business, such as power generation, food manufacturing, and water treatment. The frequency of chemical disasters occurring in developing countries 2012-2016 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. [53]

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

In current times, there is 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 summarised on page 7, that are then applied in the context of an ISO 31000:2009 risk management process. (See Figure 3.) From an operational perspective, successful risk management comes from applying layers of protection throughout the process life cycle (design to decommissioning), starting with 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 minimize process hazard risks.

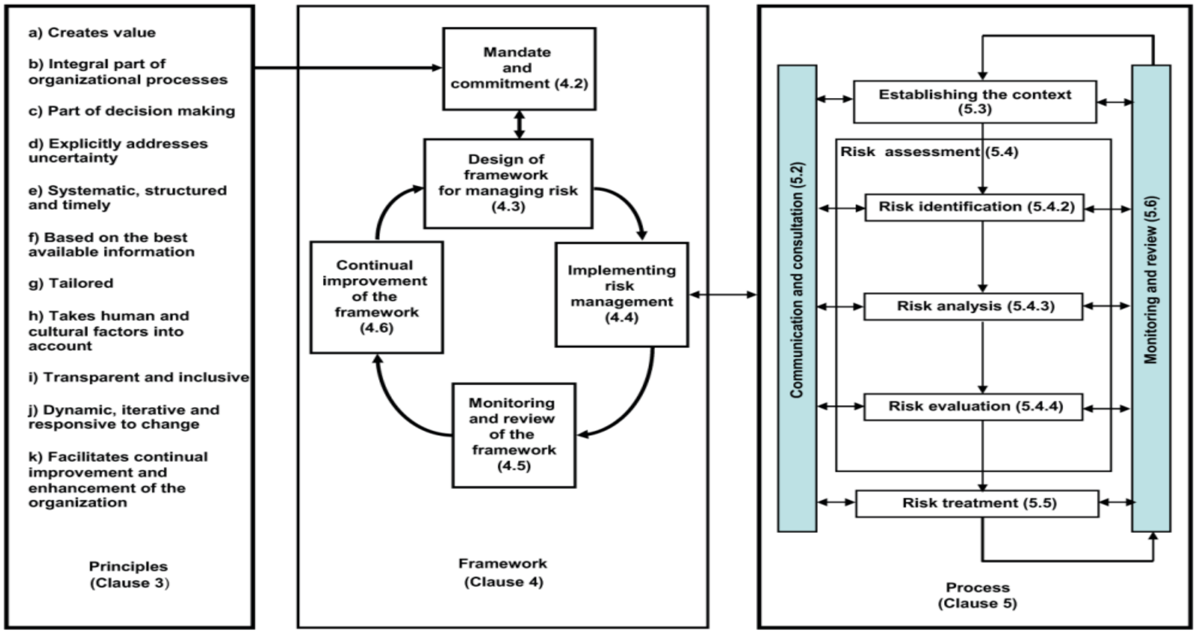

Figure 3. Relationship between the risk management principles, framework and processes (ISO 31000:2009 Risk management – Principles and guidelines) [22]

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

The hazardous industries understand in principal how to manage chemical accident risks. Then why do these industries continue to repeat failures of the past and have accidents and sometimes disasters? A study of accidents of the last few decades and the work of numerous experts in manmade 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 computerization of business processes, have brought benefits but also come with their share of risks. These risks are particularly notable for manmade risks where small changes to complex systems can unwittingly remove barriers to initiation or propagation of a potential hazard event. on the system out their own share of come with also.

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[13][14]). A number of high profile technological disasters occurring after 2000 have challenged some longtime risk management experts to identify the patterns underlying the repeated failures behind the latest round of technological accidents, building on the original work of Perrow[36] [36] and Rasmussen on managing risk in complex systems, among others, in the 1970 with new approaches. [39] Hollnagel et al. have introduced the concept of "resilience engineering" for technologically complex industries. They look at risk management from the organizational 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 the 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." [18] Klinke and Renn suggest that "risks must be considered as heterogeneous phenomena that preclude standardised evaluation and handling" in their 2006 paper describing government's potential role in managing systemic risks. [25] Le Coze proposes that new analytical models for safety assessment to take into account the dynamic and systemic aspects of safety. [27]

Kletz commented on the pattern of corporate memory loss in UK companies as far back as 1993. [24] More recently, Baybutt's 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." [3] Wood et al. [53][53] also found that where probable causes of the accidents have been ascertained, they are most often associated with predictable circumstances where control measures were insufficient due to 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. [11]

The research of Taylor et al. [44] collated and synthesized circumstances and causality associated with twelve 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 which ensure that process safety risks are properly assessed, and the influence of commercial interests, as among key forces that shaped the events leading to the accidents. Arstad and Aven [1] point out, "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 outlines a High Reliability Governance model based on multiple engagements between government and industry actors, that continually reinforces common performance expectations and a high level safety culture. [6]

A large part of scientific studies of technological disasters focus on big well-resourced organisations. But it is a fact that many serious accidents around the world originate in small and medium enterprises that are operating fairly simple processes (e.g., warehouses, fuel distribution). [11][12][13] [42][49][21] [42][49] While they are not all "disasters", 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.[50] In addition, there is some evidence that government and society unwittingly, for sometimes very good motivation, accept more risk when it concerns small and medium-size businesses. These companies are often 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 that have been the site of several accidents with multiple fatalities in the last 5 years within the EU. [10][53] Moreover, recent tragedies, such as the disasters of Tianjin, China (2015) [42] and West, Texas (2013) [49] indicate that in these cases, that 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 twelve types of underlying causes 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 manmade 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 dimensions that are sometimes not covered well 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 twelve underlying causes are as follows:

- **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. Except for high cost accidents reported by insurance companies, there are no published statistics on accident frequency. International media picks up only high profile disasters that are a small fraction of chemical accidents that happen every week. Moreover, as noted by Quarantelli [38] , 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.

- **Failure to manage across boundaries.** The organisations and individuals in charge of chemical accident risks usually define the challenge 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 internal to organisations as well as across industrial sectors, professional disciplines, and international boundaries. [10] [11] Chemicals risk management in industry has traditional been assigned to chemical and mechanical engineers who have little training in human and organizational factors. Government assigns monitoring and enforcement on the basis of who is affected, i.e., on-site workers (labour authorities), off-site communities (civil protection authorities), or the environment (environmental authorities). The large multinational industries, such as oil and gas, and chemical manufacturing companies, have little exchange 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 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.

Distant leadership and optimization strategies: a recipe for organizational 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 insufficient prioritization of safety over profits . Two people were killed and eight injured. The state of Victoria was left without its primary gas crippling industry and the commercial industry with an estimated economic loss of at around A$1.3 billion. [20] Similarly, the lack of adequate oversight of operations at a fuel storage terminal, coupled with poor intercompany communication exchange was considered to a leading cause of the devastating **Buncefield explosion and fire** at the Buncefield fuel terminal, United Kingdom**,** in 2005 [47]. 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 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. [21]

- **Failing to learn lessons from past accidents and near misses.** There is substantial evidence that neither government nor public authorities are sufficiently learning from past accidents. Taylor et al. [43] note that that failure to learn was recurrent in organisations involved in some of the significant manmade disasters of the last thirty years in Europe and elsewhere. According to the study, barriers to learning were related to culture, 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 systematic study of past accidents both occurring on the site and elsewhere. Learning from one's own accidents (in one's organisation or jurisdiction) is important for diagnosing specific weaknesses and trends. Learning from relevant accidents that occur on other sites and in other locations is essential for mapping all possible pathways that could lead to an accident. Even when problems are recognized, 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, government will respond with new, or stricter, but not necessarily better, regulation.
- **Social drivers, including economic trends.** Avoiding situations where judgement is clouded by other considerations is a long-standing challenge of risk-management, as evidenced by the accidents in BP Texas City [5] and the explosion and fire at the Macondo offshore drilling platform [48]. 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 aging 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 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 of developing countries.

Economic pressure is a particular social driver that can put gains in chemical process safety at risk, particularly in modern times 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 thin. However, there also various trends in profitable companies, such as optimization (operational efficiency) and the drive towards increasing shareholder value, that can undermine risk management when they are applied without due consideration of impacts on risks.

When industry and government both fail to learn lessons from past accidents. Even major disasters are ignored and forgotten. A case in point was the massive explosion involving ammonium nitrate fertilizers that occurred in **West (Texas), USA in 2013** that killed 15 people and destroyed 140 nearby homes. This incident was preceded by some well-known disastrous explosions involving ammonium nitrate fertilizers, in particular, Oppau, Germany, 1921 (>500 deaths), Texas City (Texas), USA, 1947 (581 deaths, > 3000 injuries) and Toulouse, France, 2001 (29 deaths, >2500 injuries). It appears that lessons from prior accidents* about handling ammonium nitrate fertilizers had not been taken into account in either industry practices or fire protection laws [5]. Furthermore, the potential off-site consequences of an ammonium nitrate explosion were ignored by the prevailing environmental regulation that only had jurisdiction 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.[49]

- **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 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. “ [1] This situation is echoed in a number of the highly visible chemical accident disasters over the last few decades (e.g. BP Texas City [5], Buncefield [21] , Macondo [48][48]). Risks are not perceived as risk but problems to work around. The prevailing trends are quickly replaced by new trends, existing technologies are quickly replaced by new technologies. Sites change ownership with considerable frequency [23] accompanied often by significant change in management policies, work patterns, safety culture or other structures that guide norms of behavior, and also contributes to an increasing decline in the corporate memory of accident risks. [33] 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, but also political, commercial and economic dimensions. As noted by Ruifeng et al., Process control and safeguarding equipment are more complex, thereby increasing newer risk which is often unforeseen. [41] Both Mannan and Quarantelli also indicate that a correlation exists between scale and complexity of process plants and major incidents. [29] [38] Yet these and other modern trends are having significant consequences on safety and security, whose long term impacts are still not fully understood. Deeper understanding requires a multi-disciplinary approach even though the job market is exhibiting a tendency for increasing specialization.

- **Automation and information technology dependencies.** Twenty years ago Quarantelli [38] 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 distinctly new danger. Indeed, 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, 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 [26] Moreover, as Taylor et al. 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. [43] A further concern has emerged with the vulnerability of IT 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.
- **Failure of risk management and risk assessment.** The EU eMARS database [11] and the U.S. Chemical Safety Board ([48] [49], for example) have produced many reports of recent past accidents that application of actions within the hierarchy of risk management controls could have reduced the likelihood that the event occurred or the severity of its impacts. 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 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 following 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 inattention to inherent safety in which processes are designed without considering opportunities for risk reduction (chemical substitution, limiting volumes, exposure, etc.). This failure are sometimes attributed to various business and organizational trends cited in this paper, e.g., business climate and economic trends, organizational change and staff reductions, complexity, and sometimes a loss of focus (complacency or "organizational drift" [43]) but in other industries, particularly non-chemicals businesses and small companies, other factors such as lack of awareness and education, are stronger influences.

- **Corporate disconnect from risk management.** The globalization of hazardous industries has increased both the physical and mental distance between headquarters and the sites they manage. Headquarters staff lose a tactile understanding of how sites are experiencing chemical accident risks.

Accidents that resulted from complexity and complacency working together.
Macondo Oil Drilling Platform (Gulf of Mexico, 2010) The Macondo disaster of April 20,2010, 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. [48]
BP Texas City (USA, 2005). On March 23, 2005, a series of explosions occurred at the BP Texas City refinery during the restarting of a hydrocarbon isomerization unit. Fifteen workers were killed and 180 others were injured. [5]
Experts have noted that these two accidents were stupendous organizational failures with remarkably similar causality, including: a) multiple system operator malfunctions during a critical period in operations, b) not following required or accepted operations guidelines ("casual compliance"), c) neglected maintenance, d) instrumentation that either did not work properly or whose data interpretation gave false positives, e) inappropriate assessment and management of operations risks, f) multiple operations conducted at critical times with unanticipated interactions, g) inadequate communications between members of the operations groups, h) unawareness of risks, i) diversion of attention at critical times, j) a culture with incentives that provided increases in productivity without commensurate increases in protection, k) inappropriate cost and corner cutting, l) lack of appropriate selection and training of personnel, and m) improper management of change.[6]

For example, multinational sites can pose particular complexity when the culture and policy of the management is vastly different from that which the site has been accustomed, especially if it is in a different country. [12] Corporate leaders also tend to oversimplify production safety risks (or risks are oversimplified for them)[1] [43]. 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 optimization 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 for distributing limited expertise across many sites, so that access to critical safety expertise is proportionately less available to sites. This latter phenomenon has been considered a significant factor in the Longford accident [20] as well as the catastrophic fire which occurred at the Buncefield storage site, Hemel Hempstead, United Kingdom in 2005. [21]

- **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 ensure that training and expertise are adequate to the responsibilities associated with the risk. This situation is particularly acute in developing countries where the hunger for economic growth outweighs other decision factors. In many cases, risks are not so much accepted as ignored, encouraged by a historic lack of transparency in the political classes or society as a whole. When considered in context the fatal accident risk due to major accidents is also relatively small when compared with the risks due to poverty, disease, road traffic accidents and therefore may not receive the attention it deserves as a risk which is readily mitigated. The Enschede (The Netherlands) fireworks accident of 2000 [31]and the accident of West, Texas (USA) [49] are notable examples where a lack of appropriate risk communication and awareness were significant contributors to these disasters.
- **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 infrastructure that underpin both public and private services is reaching the end of its normal lifetime. [38] 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. The physical infrastructure can also be degraded due to age or neglect, a key factor contributing to the catastrophic explosion and fire at the petroleum oil refinery at BP Texas City in 2005 [5]. In many developing countries, it is common to

What can happen when government is complacent. The disastrous fire and explosion event 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 in 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 recognized safety standards were applied nor that workers had been trained for handling hazardous goods. In addition, to causing 165 deaths people and injury to nearly 800 people, 30,000 people in the surrounding community were evacuated. [42]

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 and also 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.

- **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 prioritized. Society as a whole exhibits a high risk tolerance due 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 their companies may have sites in these countries and their citizens may be customers of their products. However, even in developed countries, there is also a recognized 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 [20], and in New Zealand following the mining accident in 2010 [40]
- **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" [43], 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 enforcement and risk management. Notably, there is 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.

3.14.3 Implications for scientific study in future

The main topics that emerge as areas for further study and experimentation for years to come are listed and described below. Many of them are already the subject of projects in research institutes and collaborations within the international community. However, it is widely recognized 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:

- **Motivating corporate and government leadership.** New models for 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 to (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. Fears that the process industries could potentially have parallels to the banking crises (2008 onwards) of poorly understood risks, triggered the development of the 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. [32]
- **Systematic accident reporting, data collection and exchange.** There needs to be a concentrated effort to build national and international chemical accident registers and 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 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 government to foster risk awareness and sensitivity among citizens. An informed safety-sensitive society can help support a broader mandate to insist that companies to 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 heightened emphasis on incorporating as soon as possible lessons learned from past events and audit findings on deficiencies in risk management into process hazard assessments and the safety management system.
- **Risk management in SMEs in the chemical business.** There are subcategories of SMEs in the chemical business and they each have elevated risk for different reasons. The most challenging intellectually are the SMEs who know their risks and take care to manage them but they still have accidents. More study is needed on why SMEs have accidents, including geographic and economic differences that may influence these risks, and on strategies to reduce them.
- **Risk management in non-chemical businesses.** Similar 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, 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. [43] Travers [45]) are already proposing models for assessing risks associated with complexity. These models need to be tested and developed further. In addition, research to characterize and quantify various emerging risks, included those associated with increasing use of automation and 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 help reduce the most common violations of safety management principles, in particular:

- **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. [28] 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 and remember. Corporate memory loss, across-industry, reporting is not enough. A greater investment is needed in projects to develop strategies to learn and remember, with a particular emphasis on industry/ government /academia collaborations. According to Patterson, both industry and government struggle with barriers that tend to undermine systematic extraction and communication and lessons learned and there needs to be renewed effort to overcome these barriers. [35] As noted by Hailwood [15], companies operating major hazard facilities should establish systems that not only ensure reporting and learning from their own accidents and near misses, but also through the 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 collect and document this knowledge and make it accessible to third parties.

Renewed effort is needed to ensure 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 individual to a site. Few sites have exactly the same risks, even if they produce the same stuff, since physical characteristics of the location, structures and equipment are an important part of the risk. Considerable future mechanisms are needed to make good management practice for all kinds of operations and equipment available in an easy to read form, taking account of the many different languages in which they might be needed.

- **Access to risk assessment competence.** Both operators of hazardous sites and the regulators need to know the type and severity of accidents that could occur and a realistic understanding of the control measures needed to ensure that the risk of such accidents is minimized. 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 of appropriate expertise.** The industry and academics need to continue to push for standardized process safety curriculums associated with chemical engineering and chemistry, in particular, as well as to some degree in environmental management and other related disciplines. 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 U.S. and process operations need to be adjusted accordingly. [55] 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 for identifying and managing risks in design and daily operations.

EU industry and government must share responsibility for reducing chemical accident risks in developing countries, with special emphasis on:

- **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, UNEP-OCHA, and 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 only possible with substantial commitments involving also UNDP, UNITAR, 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 OECD [34] and UNEP [52], already exist to guide developing countries on how to build towards a comprehensive and effective chemical accident risk prevention and preparedness programme. The clear next step is to identify and to deploy mechanisms to provide significant and sustained support to countries ready to take big 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 [51]) have reported increasing success with such approaches but they are barely implemented for chemical accident prevention programmes in regions like Asia and Africa.

- **Improving performance measures for interventions.** Fund administrators generally lack objective measures for evaluating good candidates for chemical accident prevention programme for support, targeting specific needs, and arguing for continuation of support will 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 in the JRC [2], can lead to better targeting of such initiatives. These could also be useful for developed countries.

Conclusions

Recent accident trends give evidence that the world is nowhere near reducing the risk of such accidents to acceptable levels. While developed countries have shown marked improvements, particularly in reducing averaging 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 misfortune combinations of events, but very often may be due all or in part, to incompetence, lack of awareness, or outright negligence. Many experts are exacerbated that management practices and attitudes are so vulnerable to other influences and resist improvement.

In sum, 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 the stakeholders stick to their traditional rules is not going to fix the problems at hand. 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, particular in the social sciences, need to find their way into both industry and government approaches to chemical accident risk.

- **Innovation.** The recommendations in this paper suggest a paradigm change in the way the EU and the developed world in general approaches chemical accident risk. Solutions must encompass a broader vision of risk ownership and boundaries of influence, recognising that industry's role does not end beyond the fenceline, 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.

- **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 in chemical accident risk and ownership implies both a certain responsibility and power to prevent it. This finding in turn requires that the new approach to controlling chemical accident risks is to change culture with education and awareness.

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