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Challenges and opportunities for assessing global progress in reducing chemical accident risks

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ABSTRACT

This paper gives the current outlook on assessing progress in reducing chemical accident risk from a global perspective. At the moment, there are very limited data collected for assessing the status of chemical accident risk globally. There are some sources of data on chemical accidents in government and industry that might be used to estimate the frequency and severity of some types of events, but they fall far short of providing a complete perspective that covers all chemical accidents occurring in industry and commerce globally. The paper includes a discussion of existing and potential measures for assessing this risk using accident loss data. It also argues for evaluation methods that estimate the prevalence of certain risk factors, for example, using patterns of causality or indicators of the strength of risk governance. The heterogeneous nature of chemicals, the infinite ways in which chemical engineering transforms chemicals into products, and the vast infrastructure of road, pipelines, ships and railways, facilitating product distribution, are intrinsic to the challenge of assessing global chemical accident risk and predicting the next catastrophe. The paper describes the data that are currently available and their limitations for obtaining a picture of risk from chemical accidents worldwide. It describes the various obstacles to measurement of chemical accident risk situation across industries and geographic areas and identifies ways in which policy makers could overcome them over time.

1. Introduction

Recently, with the advent of the Sendai Framework for Disaster Risk Reduction, the Better Regulation Agenda of the EU [1], as well as initiatives in OECD [2] and various countries to justify the costs of regulation, attention has returned to measuring the effectiveness of government programmes, including those that target reduction of chemical accident risks. These initiatives have stimulated some reflection among EU and OECD communities of government experts on how to measure the impacts of regulation of chemical accident risk and whether the regulation is effective in reducing these risks. Discussion on this topic has also raised awareness concerning the lack of credible performance measures to improve policy decision making and allocation of resources to this policy area.

Chemical incidents are significantly different from natural hazards and even distinctly apart from other kinds of well-known technological disasters, notably in the nuclear industry and aviation. Unlike these technological disaster types, the term “chemical accident” is not associated with a specific industry. Rather, significant chemical accident hazards are present in a wide variety of industries characterised by vast differences in the substances, processes, technology and equipment that create the risk. Chemical accident risk consists of several components and therefore, understanding accident causality, i.e., why chemical accidents happen in the first place, is critical to effective risk management and finding dependable means to measure risk management performance. Moreover, safety culture and expectations surrounding chemical process risk management among operators and citizens alike in any one country will also affect the level of risk. Hence, measuring performance in reducing chemical accident risk in any one country, or in many countries collectively, requires an approach that takes account of the several factors that influence it at local and national level.

Collecting and analysing data to understand chemical accident risk is not a new phenomenon. By the 1980s a number of chemical companies were already studying their chemical accidents to understand their risks. In 1984, the European Commission began collecting chemical accident data reported by its Member States in accordance with the first European Union (EU) Seveso Directive (82/501/EEC) in the MARS, now eMARS, database [3]. By the 1990s, it was accepted widely that collecting data and accidents and near misses were important inputs to understanding weaknesses in the risk control system and correcting them. At this time, some databases (such as MARS) became public or were available by subscription. The primary purpose of these databases was to foster learning

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from incidents. With the advent of the Internet considerable data and information on chemical accidents has been made public to facilitate dissemination of lessons learned.

It is a fact that the nature of chemical accidents poses significant challenges to measuring progress in reducing this type of risk. Tracking incident frequency and severity of incidents over time appears theoretically to be a straightforward way to obtain risk numbers. However, obtaining enough data to translate this theory into reality for chemical accident risk is not and never will be practical. Moreover, chemical accident statistics only measure disastrous failures that became accidents. They cannot measure the disastrous failures that could happen but have not happened yet.

Indeed, the presence of chemical accident risk might be underestimated by solely aggregating accident statistics. Similar to natural hazards, the years that pass without a serious chemical accident are not a sign of reduced risk, but simply evidence of the role of probability. Moreover, the use of chemical accident statistics to represent risk from all chemical hazard sources is a gross oversimplification. Serious chemical accidents are relatively infrequent and of very diverse origin in terms of substance, circumstances, and the dynamics that cause harm. Hence, data aggregation produces only a very general measure that masks large variation in chemical accident causes and exposure to accident risk across industries and geographic regions.

Measuring performance in reducing chemical accident risk is complicated. The simple use of frequency and severity of past accident is not by itself a solution for global assessment of chemical accident risk. National governments require more information to understand their industrial risk and target their interventions to reduce them. As an extension of the national risk picture, it can be concluded that the global assessment of chemical accident risk should also reflect a broader range of inputs.

The paper argues that the better path is for the expert community to examine a variety of options in parallel, producing quantitative and qualitative information that in combination can give a more precise and accurate picture of progress and ongoing and future challenges. Government and industry are already using alternative metrics for prioritising process safety interventions, such as industry safety performance indicators, hazard ranking systems, and risk governance measures. These systems can serve as a rich source of ideas for different types of data measuring global progress in reducing chemical accident risks.

The paper will describe these challenges and suggest some starting points for developing solutions. It will begin with a description of how chemical accidents differ from other types of natural and technological disasters and therefore pose particular challenges for performance measurement. It will then describe current data available for tracking incidents and how they might be improved to support assessment of global progress in reducing chemical accident risks. Finally, it will describe additional data and alternative models for measuring process safety performance and also for evaluating hazard sources.

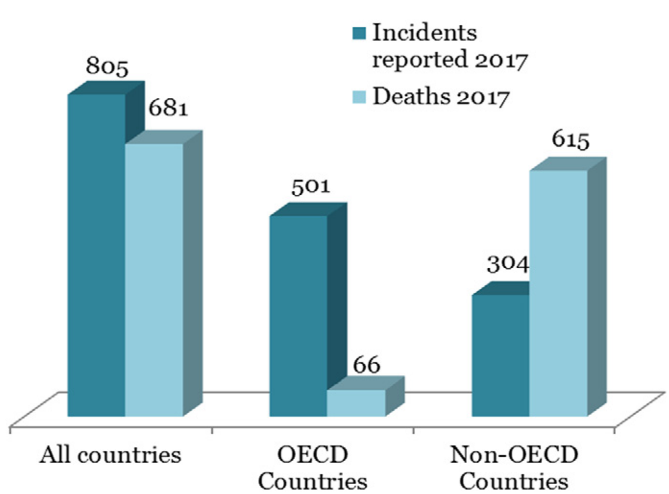

Fig. 1. Chemical incidents occurring in 2017 12 reported in the global media [4].

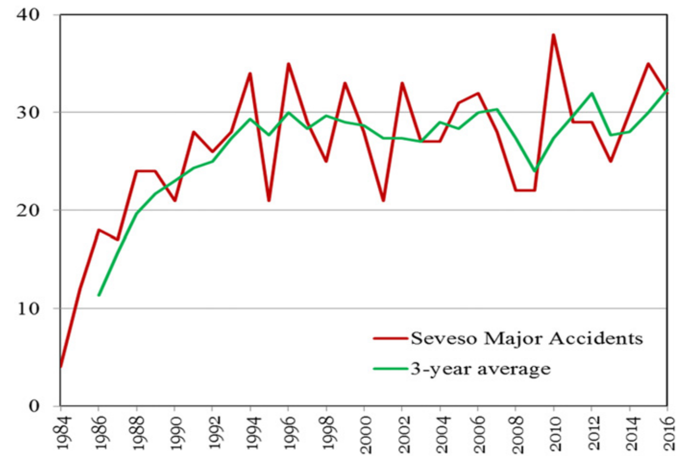

Fig. 2. Major chemical accidents reported to the EU eMARS database 1984–2017 [5].

This paper presents cumulative findings and conclusions from research in chemical accidents conducted by the European Commission's Joint Research Centre (EC-JRC). The EC-JRC manages the European Union's eMARS chemical accident database but also has produced multiple studies of chemical accidents over the years and maintains a global chemical accident database based on reports in the media worldwide.

2. What past accident data tells us about chemical accident risk

Chemical accident data provide an essential and fundamental contribution to forming the chemical accident risk outlook in any one country and across countries in a region as well as at global level. The occurrence of just one chemical accident is information about the existence of actual risks in the industrial sector. A number of serious accidents that occur in the same time period gives even more evidence of the presence of risk. If a country has a number of serious chemical accidents each year, it can be assumed that its industrial risk is definitely high.

Past accidents can also provide diagnostic information. If some accidents have common features, e.g., location, or type of industry, equipment, substance, or cause, this commonality may be an indication of a failure trend. These data are extremely useful in evaluating the potential risk in a country, especially if the country has already identified its chemical hazards and the characteristics that give them lower or higher risk profiles. For every chemical process, handling and storage operation, there are a number of conditions that must be maintained to prevent a chemical release. Any modification in those conditions changes the risk. Studying aggregated data of chemical accidents can identify patterns in the circumstances surrounding failure to prevent chemical releases or sufficiently mitigate their impacts.

The European Commission's Joint Research Centre (EC-JRC) has reviewed a wide range of chemical accident data from different sources in recent years. According to its findings, chemical accidents are still a relatively frequent occurrence in all industrial countries and raise important questions about the adequacy of disaster risk reduction efforts. Fig. 1 represents information in media reports worldwide on chemical incidents collected by the EC-JRC. The data show unplanned releases of dangerous substances occurring on fixed sites, offshore platforms, transport of dangerous substances, and pipelines during the 2017 calendar year. These figures are significant in that they indicate that generally chemical incidents are relatively common in all parts of the globe.[1] They also show that chemical

[1] Due to variations in media reporting across countries, and limitations of keyword searches and web crawlers, media reporting does not represent a complete picture of all incidents that have occurred around the world. In many cases the details provided in the report are also limited. Still, media reports tend to be consistent and reasonably reliable when citing major impacts that are already available within the reporting window (hours and sometimes days following the incident), especially deaths, injuries, evacuations and environmental contamination.

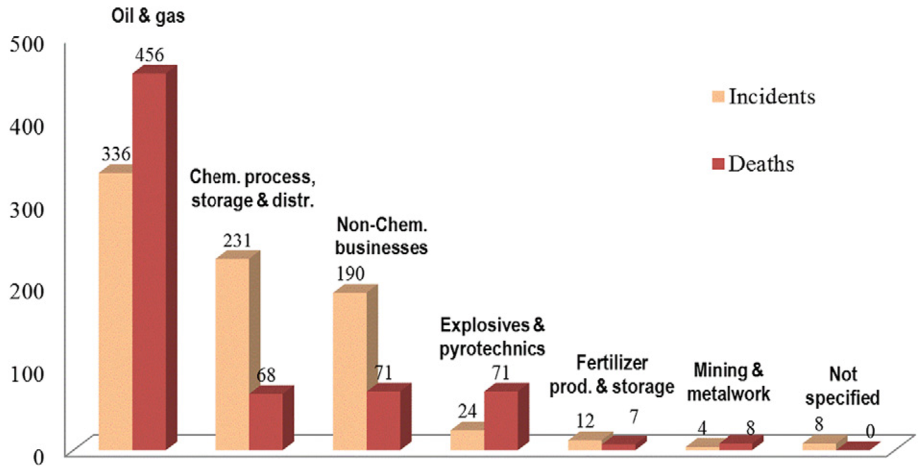

Fig. 3. Chemical accidents and associated fatalities reported in the global media by industry sector in 2017 [7].

accidents continue to kill hundreds of people every year and at higher rates in some areas of the world than others.

On the one hand, as Fig. 1 shows, OECD countries, representing the world's most industrialised economies, experience far less deaths from chemical accidents than non-OECD countries. These data show that efforts to control chemical accident risk in these countries have been largely successful in reducing deaths and injuries from the vast majority of chemical incidents that occur. On the other hand, this positive trend is not necessarily reflected in a reduction in the frequency of high impact chemical catastrophes. A list of disasters occurring in the past 10 years is evidence of the persistence of catastrophic risk from chemical hazards in industrialised countries. Some notable events include the Deepwater Horizon oil spill in the Gulf of Mexico (USA, 2010), the Ajka alumina sludge spill (Hungary, 2010), the ammonium nitrate fire and explosion in West Texas (USA, 2013), the rail tank car explosion of Lac-Mégantic (Canada, 2013), and the explosion of the explosion of the Arkema chemical plant in the wake of Hurricane Harvey (USA, 2017).

Moreover, while the rate of serious chemical accidents (e.g., vs. growth in production volume or GDP) may have decreased in the last 30 or so years, there is evidence that absolute exposure of populations to chemical accident risk has not decreased in any way. Industrialised countries continue to experience serious chemical accidents with regular frequency. These serious accidents do not necessarily qualify as full-blown disasters, but they still cause multiple deaths, or otherwise significant impacts on communities or the environment. These events are exemplified by the fire and explosion at the BASF plant (Germany, 2016), the warehouse fire in West Footacres (Australia, 2018), and the explosion of the LPG tank car on a highway outside Bologna (Italy, 2018) are just a few examples. These incidents, and others like them, are a clear sign that chemical accident risk in developed countries remains a constant concern. As further evidence, Fig. 2 shows that major chemical accidents reported to the EU's eMARS database have hovered around an average of around 30 per year since 1994.[2]

These findings are hardly surprising given that OECD countries make up more than 50% of global GDP and continue to grow. Chemicals and innovations and chemical engineering are at the core of modern industrial production and also support the vast majority of commercial processes. All these activities and industrial growth in general, are also dependent on a large supply of fuel (a class of substances that are generally extremely flammable, or at the very least, toxic to the environment). Notably, as Fig. 3 shows, the high hazard industries, particularly oil and gas industries, and chemical processing, and related storage and transport industries, remain high hazard industries.

3. Limitations of accident data in understanding chemical accident risk

While the above section illustrates that chemical accident data in aggregate can provide important insights into chemical accident trends, it would be erroneous to rely on aggregate chemical accident data alone as an indicator of global and national performance measure. As noted in Text Box 1, The practical limitations of data collection, the low frequency of serious accidents, and the multiplicity of hazard sources and how they change over time, are all aspects that limit characterization of risk relying solely on past accident history. While existing data sources can be improved to provide more valuable and consistent information, there are some inherent limitations that cannot be overcome.

3.1. Relatively few dedicated databases for chemical accident events

To produce a global assessment of risk, a global database on major chemical accidents occurring around the world (not just catastrophes) would be required. As a whole, there are very little publicly available data on chemical accidents worldwide. While the EC-JRC has begun assembling a global chemical accident database from media reports as part of its ongoing chemical accident research programme, an official international database for analysing global chemical accident trends does not exist and is unlikely to be established any time soon. Relatively few countries and industry organisations around the world maintain dedicated chemical accident databases, even though the number of countries and organisations collecting chemical accidents has increased somewhat over the last decade.

3.2. Fragmented and disjointed data

The way accidents are described and classified in terms of causal trends and impacts is largely driven by government requirements[3] and industry initiatives behind the data collection. For example, the EU eMARS database collects data on chemical accidents occurring in over 12,000 fixed facilities qualifying as high hazards under the Seveso Directive. As a source of lessons learned from chemical accidents, it is a valuable resource. However, for assessing chemical accident frequency and severity, it is incomplete, excluding incidents in pipelines, transport and hazardous facilities not

[2] If the 13 countries that acceded to the European Union since 2004 are excluded, the average per year drops from 31 to 27.

[3] This discussion excludes "incident notification" databases that are composed of unverified notifications to authorities via emergency hotlines or to fulfil a pro form legal obligation to inform the authorities if a release of a dangerous substance has exceeded a certain threshold.

Text Box 1
Why chemical accident risk reduction is difficult to measure using accident data.

- **Hazardous sources vary considerably** due to different industries, substances, processes and equipment. Aggregated statistics can be misleading.
- **Chemical accident risk is not a stable figure**. Numerous variables that influence chemical accident risk makes it more likely that actual risk levels fluctuate significantly over time.
- High severity chemical accidents are **low frequency events**. Accident data can greatly underestimate actual risk.
- Chemical accident risk sources distributed over many industries and geographic areas. It is challenging to have a complete picture.
- **Data on chemical accident causality mainly belongs to companies**. Data on what caused the accident are usually not in the hands of government.
- **Loss data** following an accident belongs to many actors and **is difficult to collect and quantify**.

covered by the Directive. As another example, the U.S. collects data on federal and state-regulated pipelines, but does not maintain a reference database of chemical accidents in its 16,000 fixed installations covered by its risk management legislation. The International Association of Oil and Gas Producers (IOGP) publishes annual aggregate chemical accident statistics by type of activity, impact, causal factors, geographic region, and other variables but the data only represent the companies represented [6]. As such each database has its own criteria and rules in regard to the type of information collected from its membership and not the entire industry sector. Besides, each database makes its own rules about which events are included, what information is collected, and how the information is presented, whether quantitative or qualitative, and in what level of detail.[4]

3.3. Incomplete data on chemical accident impacts

Past accidents also provide valuable input on the range and scale of impacts that different chemical accident scenarios can potentially produce. To date, fatalities and injuries are the only impacts that are consistently collected and quantified in publicly available chemical accident databases. They are far less reliable in regard to providing information on exposure to other types of impacts, often leaving out entire categories (e.g., social and economic impacts), or failing to quantify others (e.g., environmental accidents are also an important source of information for understanding the range and severity of impact and community impacts). Table 1 lists strengths and limitations of various impact data currently available in public databases of chemical incidents.

Table 1
Strengths and limitations regarding data collected for different types of impacts associated with chemical incidents.

Type of impact data	Strengths and limitations
Human health impacts	Historically, fatalities are always identified and recorded. Injuries are also usually quantified, but the precision in regard to number and severity increases with the severity of the accident.
Environmental impacts	Environmental impacts are reported using a variety of denominations to quantify the impact (e.g., cubic meters, length of a river, duration of the power outage, etc.) and rarely include costs of clean-up and restoration or economic costs from loss of the resources.
Property damage	Data on cost of on-site property damage are often provided, but not as reliably as human health impacts. Off-site property damage, when it has occurred, is more often than not excluded from reports, rarely appearing in either accident databases or insurance company statistics. Sometimes the media will make an estimate for a particularly prominent accident. These impacts are sometimes reported with estimated quantities in the media. For large incidents, the data can also be found in annual insurance reports.
Evacuation and shelter-in-place	These data are frequently provided as estimates and they are often sufficient for estimating severity of this aspect, but they cannot be easily summed for aggregating effects of major accidents over a period of time.
Social disruption	Disruptions to roads and public utilities are among other impacts that generally are ill-defined in terms of both what they include and how they are quantified (e.g., hours of disruption, population size disrupted, etc.) The eMARS database is possibly the only industrial incident database that includes fields for these impacts but they are not well--defined. For example, eMARS includes a category for “schools, hospitals, institutions” but is not indicated if this means evacuation, closure, overcrowding, or other type of disruption.
Economic impacts	Economic impacts from temporary and permanent shutdown of product lines and sites are a significant impact of many accidents. These data are usually only provided in investigation reports and the media.
Long-term health and social impacts	These effects may include injuries and/or acute exposures with long term effects, mental health impacts, as well as long term effects on the local economy and social life. There is an increasing awareness that such impacts are also important to consider, but collecting data and studying them remains in the domain of researchers. These effects can only be observed long after an accident has occurred and cannot easily be a captured in an accident investigation that generally takes place immediately after the event. However, research may eventually produce measures or qualitative criteria that might be used to signal the potential for long term effects.

3.4. Only a partial representation of potential risk

Serious chemical accidents are generally low probability events. Even across a region as large as the European Union, the annual number of serious accidents is not high enough to give very strong statistical signals about the expected frequency of serious accidents in future, where they might occur, and the type and severity of impacts. In addition, the likelihood and severity of a chemical accident are influenced by a large number of variables that can change from one moment to the next. Very often the extent of the impact is dependent on the time of day or day of week. For example, if people are absent, who would normally be present in a particular location, the fact that they are not affected skews the impact of the event in terms of statistics. It is important to recognise that chemical accidents are stochastic events which cannot be fully evaluated with a simple measure of counting the occurrences of a particular scale. While the presence of the chemical hazard is constant for an individual activity, the circumstances surrounding that activity change continually.

In any case, with some exceptions, chemical accident data on a national basis may be insufficient for reaching any conclusion at all. The average frequency of events in any one country across a given time period of say, one, five, or ten years, tends to be extremely low in many countries, especially in small countries and those with a low level of industrialization. Exceptions include large industrial economies where the number of major accidents and near misses reported each year is sufficient to allow identification of some industry trends, and emerging economies where serious accidents occur at alarming frequency because industrialization is outpacing the country's ability to control the inherent risks.

3.5. Not representative of all chemical hazard sources

A second complication arises from the heterogeneity of the industrial and commercial activities that represent chemical hazard sources. There

[4] This paper only refers to public sources of accident information. It can, however, be assumed that private sources, should they become available, would have the same limitations.

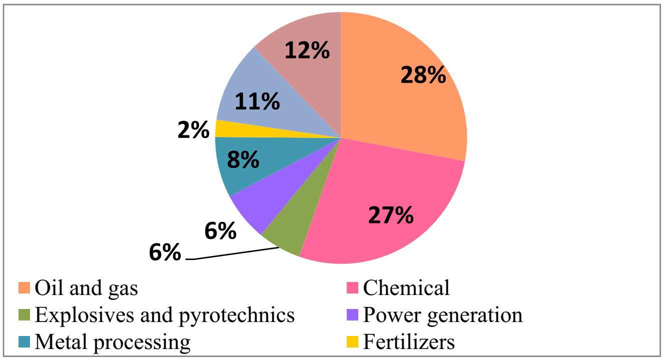

Fig. 4. Distribution of Seveso Directive sites (high hazard fixed facilities) in EU and EEA countries in 2014 [7].

are many different types of accidents in different industries with different causality to consider these data reliable. Past accident data are particularly poor sources of information on risks associated with industries that are relatively new or whose operations are small and not very numerous.

There are hundreds of processes in oil and gas or chemicals processing industries alone that involve the use of flammable and toxic substances in high volumes. Such substances may be present in land-based establishments (also known as "fixed facilities"), pipelines, transport by rail, road and water, and offshore oil exploration platforms. Explosives industries, involving manufacture and/or storage of explosives, fireworks and other pyrotechnic articles, are also prominent sources of chemical accident risk. The high use of dangerous substances, such as cyanide and arsenic, in metals processing also has elevated the mining industry into the high risk category.

In addition, numerous other industries that are not part of these hazardous chemicals industries also can be sources of chemical accident risk. Sometimes known as "downstream users", they are industries such as food production, power plants and metal plating that use dangerous substances in large quantities for refrigeration, fuel, metal treatment, and various other specialised uses. The latter types of activities are particularly challenging to a society's overall risk management strategy because these hazard sources may have lower awareness and be less knowledgeable about the dangerous substances they use than those industries whose core business involves exploitation, manufacture, storage or handling of them.

Fig. 4 shows the distribution of the ~10,000 Seveso Directive sites (high hazard fixed facilities) in the European Union as reported by countries in 2014. Of these sites, 61% belong to the chemical manufacturing, explosives and pyrotechnic, and oil and gas industries sectors, while the remainder are in other types of industries. A site is identified as a Seveso site if dangerous toxic, flammable or explosive substances are present above certain threshold quantities. Preliminary analysis of 2017 reports indicates more than 12,000 Seveso sites reported.

3.6. Where do we go from here? Strategies to improve our ability to assess chemical accident risk at national and global level

Given the complexity of chemical accident risk, assessing progress in risk reduction requires the implementation of many measures in parallel. While collection of chemical accident data provide a fundamental input, understanding of risk and exposure will improve if other types of data are collected and analysed in parallel. Assessment requires strategic choices about what and how to measure and about analytical techniques to apply for interpreting data. Analysis can include the use of descriptive statistics, but also the application of other analytical methods such as interpolation from case studies (if this could happen at this site, it could probably happen at that site), and foresight (making educated predictions about how risk might be affected by changing markets, technology, investment resources, society and culture, etc.). Measures for global assessment may consist of a subset of these measures, or aggregations of inputs, or a collective finding from different kinds of measures applied to various regions and industries.

What these measures could be, how they could be implemented, and who should be involved are aspects that require considerable discussion among national authorities and industry stakeholders around the world. One part of the discussion should focus on how existing mechanisms for accident data collection can be improved and how these mechanisms could be somehow extended or promoted to have data coverage of geographic areas and industrial activities that are not currently represented. The other part of the discussion should be on collection of other types of data, particularly leading indicators that can provide insight into a range of factors influencing risk in a particular location or type of site.

The following are actions that could help improve the ability of countries and industries to assess their exposure to chemical accident risk, and that could be the subject of further discussion and improvement by experts at national and international level:

- Expanding knowledge of chemical accidents by promoting the collection and publication of chemical accident data in all industrial economies and in all major hazard industries
- Improving collection of impact information in existing accident databases to gain knowledge about the range and type of impacts occurring and the possibility of quantifying cumulative impacts across geographic areas and industries
- Encouraging collection of leading indicators from various sources, e.g., case studies, media, inspections statistics, that can serve to estimate the level of risk and identify specific risk factors in relation to individual operations, different industry sectors, and geographic areas.
- Recommending that national governments develop hazard profiles of industries, countries, and geographic regions, especially with relation to shared borders and shared natural resources
- Measuring the strength of risk governance and capacity by country
- Analysing recent catastrophes to identify emerging risks at national and global level and in specific industries

There are already existing models in use today for collecting each of the above data elements. The following sections describe and justify each of the above improvements and provide some examples of models for implementing them that are already available in the public domain.

3.7. Promoting collection of data on past chemical accidents in national government and industry

Currently only a fraction of industrial countries and industry sectors collect and publish data on chemical accidents and some of these only cover certain industries and types of activities. Therefore, the first step to facilitate assessment of national and global risk is to encourage the promotion of centralised reporting of chemical accidents to national governments and associations of hazardous industries that still do not have these data. Encouragingly, there are already many industrial countries that have centralised databases for at least one or more hazard sources (i.e., fixed facilities, transport, pipelines or offshore platforms). It is not certain whether there are many of these countries collect chemical accident data from all hazard sources, since not all data may be publicly available.

Media reports and insurance company figures are other sources of chemical accident data that are sometimes cited. Media reports have shown to have particular promise as an input to future global assessment as demonstrated by both the EC-JRC studies and the Work Accident Map produced by the Chinese Labour Bulletin.[5] Insurance company figures are also sometimes considered an important data for assessing incident impact trends. However, publicly available data from insurance companies tend to only be consistently available for very large disasters.

3.8. Improving knowledge about accident impacts

While the number of deaths and injuries produced from a chemical accident are routinely collected, equivalent data are not collected consistently

[5] http://maps.clb.org.hk/accidents/en#201801/201807/1821.

Economic consequences	1	2	3	4	5	6
Property damage in the establishment (C expressed in millions of €)	0.1 ≤ C < 0.5	0.5 ≤ C < 2	2 ≤ C < 10	10 ≤ C < 50	50 ≤ C < 200	C ≥ 200
The establishment 's production losses (C expressed in millions of €)	0.1 ≤ C < 0.5	0.5 ≤ C < 2	2 ≤ C < 10	10 ≤ C < 50	50 ≤ C < 200	C ≥ 200
Property damage or production losses outside the establishment (C expressed in millions of €)	-	0.05 ≤ C < 0.1	0.1 ≤ C < 0.5	0.5 ≤ C < 2	2 ≤ C < 10	C ≥ 10
Cost of cleaning, decontamination, rehabilitation of the environment (C expressed in millions of €)	0.01 ≤ C < 0.05	0.05 ≤ C < 0.2	0.2 ≤ C < 1	1 ≤ C < 5	5 ≤ C < 20	C ≥ 20

Fig. 5. Criteria for economic consequences, European Gravity Scale for Industrial Incidents [9].

for other types of impacts, including environmental damage and clean-up costs, the number of people evacuated or sheltered in place, disruption of traffic, power outages and other service interruptions, loss of production and jobs, and disturbances to product supply chains. At present the cumulative effect of chemical accidents on society cannot be quantified because of a lack of precise data on these impacts, as well as variation in the way such impacts are measured. For this reason, policymakers in industrialised countries are encouraged that many serious chemical accidents occur without death or injury, but ignore the harm that environmental, social and economic consequences of chemical accidents may inflict on local communities and business interests.

Collecting quantified data on non-human health impacts is inherently challenging because some costs are never quantified precisely (e.g., traffic and infrastructure disruptions), and other costs, such as environmental clean-up and economic losses are often borne by the private sector and in the case of large scale impacts, costs may be distributed across several organisations and may continue to accrue months or years after the event. For most of these non-human-health impacts, with the exception perhaps of evacuation and shelter-in-place, there is limited scope for standardizing quantification or overcoming obstacles to obtaining reliable estimates to support quantification. However, there is often enough information available to support impact rating that does not require precise estimates. The European Gravity Scale for Industrial Incidents (see Fig. 5) is an example of one such model that could provide a solution in this regard. The French ARIA database has been applying this scale to technological incidents for over two decades. Its scoring mechanism equates different thresholds of damage in each category with a specific level of impact from 1 to 6. The EC-JRC also rates events in its database of chemical accidents in the global media based on this same scale to classify events as limited impact, serious or catastrophic.

3.9. Collecting leading indicators to identify risk management and enforcement priorities before accidents happen

In recent years, many hazardous site operators, specifically in the chemical processing, and oil and gas industries, as well as some government authorities, are introducing systems for assessing site level risk that essentially tracks "symptoms" of potential elevation in risk. Safety performance indicators (SPIs) are increasingly used to monitor the performance of the safety management system through collection of data on pre-selected indicators. They are intended to identify potential deficiencies in the safety management system, in particular, whether prevention and mitigation measures are working as intended, root causes for deviations have been investigated and understood, appropriate corrective actions have been taken, and relevant communication to management and operations staff has been initiated [8].

Text Box 2 shows suggestions for safety performance measures proposed in various industry guidance. The inputs to the measures can be derived from a diverse range of feedback sources, depending on the measure, including data from process operations, maintenance, and instrumentation, near miss reporting, audit findings, quality control monitoring, etc. In addition to the industry sources cited in the text box, the OECD has also produced guidance on safety performance indicators for industry [12]. Company and site level SPIs are somewhat limited in their ability to provide input to assessment beyond site or company level. There is no general standard for assessment which would allow comparison or benchmarking of SPIs across a wide range of facilities, industries or countries. Currently, safety management systems are tailored to the local performance requirements and, within larger organisations, to the needs at corporate level.

However, some national authorities have also begun to apply safety performance indicators in enforcement and oversight across hazardous operations. In 1999 the Norwegian Petroleum Safety Authority established a methodology for measuring important parameters that influence safety and working environment on offshore oil platforms [13]. Similarly, the United Kingdom Health and Safety Executive tracked performance of hazardous sites in managing five ageing factors, leadership, asset register, primary containment (tanks and vessels), safety critical mechanical equipment, and resources [14].

3.10. Development of hazard profiles on the basis of relative ranking of risk factors

As a similar type of tool, hazard profiling and ranking by hazard source has become a widespread mechanism in some countries, most notably in

Text Box 2
Examples of site safety performance measures [10,11].

- Length of time plant is in production with items of safety critical plant or equipment in a failed state
- Percentage of start-ups following plant changes where no safety problems related to the changes were encountered during re-commissioning or start-up
- Number of safety critical tasks observed where all steps of the relevant safe working procedure were not followed
- Number of operating or maintenance procedures reviewed per year versus planned
- Number of deviations observed outside of established ranges in safety critical equipment
- Number of safety barriers (e.g., relief valves, cooling systems, etc.) that failed when tested
- Damage to primary containment detected when tested or inspected
- Number of maintenance or corrective measures deferred for safety critical equipment vs. number approved
- Temporary operating procedures that are ongoing
- Number of process safety related emergency response drills versus number planned

These outcomes are often divided by *expected numbers* to achieve a % compliance rate.

EU Member States, for understanding risk across many hazardous sources in a region and prioritising government intervention. Hazard profiling often entails ranking sites relative to other sites in a particular jurisdiction in relation to particular risk factors. As shown in Fig. 6, they typically combine objective risk indicators, such as type and quantity of dangerous substances, type of industry in combination with data specific to the individual site or operation, e.g. accident history, compliance record, and inspection findings etc. These ratings can be useful indicators of relative levels of hazard exposure across sites and transport lines, including sites that are showing good performance in managing risks. They can also typically identify patterns in terms of relative risk associated with certain processes or specific industry activities. Hazard profiling can also help national and local governments select different levels of attention and focus (e.g., more or less frequent inspections, changes in inspection strategy). Several national hazard rating schemes are described in the EC-JRC and UNECE joint publication on hazard rating systems in EU Member States, EEA countries, and national competent authorities under the UNECE Convention on Transboundary Effects of Industrial Accidents (TEIA) [15].

3.11. Measures of risk governance

The strength of legislation and government monitoring and enforcement programmes can also serve as an indicator of risk. A number of international organisations have developed various methods for assessing government mechanisms for overseeing chemical accident risk and evaluating their capacity for implementing improvements. In particular, the OECD Guidance on Developing Safety Performance Indicators For Public Authorities and Communities/Public [16] and the UN Environment Flexible Framework [17] offer useful guidance to measuring capacity and governance in relation to chemical accident risk. The European Commission also produces a 4-year report (formerly a 3-year report) on implementation of the Seveso Directive in EU and EEA countries that contains some indicators that could be useful for other countries as well.

While these instruments are intended for the evaluation of government programmes, the OECD Guidance on Corporate Governance for Process Safety is intended for process safety for leaders of the chemical, petrochemical, petroleum and other high hazard industries [19]. It includes a self-assessment questionnaire for evaluating site or corporate level risk governance. Some countries, in particular the United Kingdom and Finland, are known to have actively incorporated corporate leadership principles into their process safety oversight activities. Fig. 7 shows an excerpt from the survey conducted by the Finnish inspection authority, TUKES, in 2013–2014.

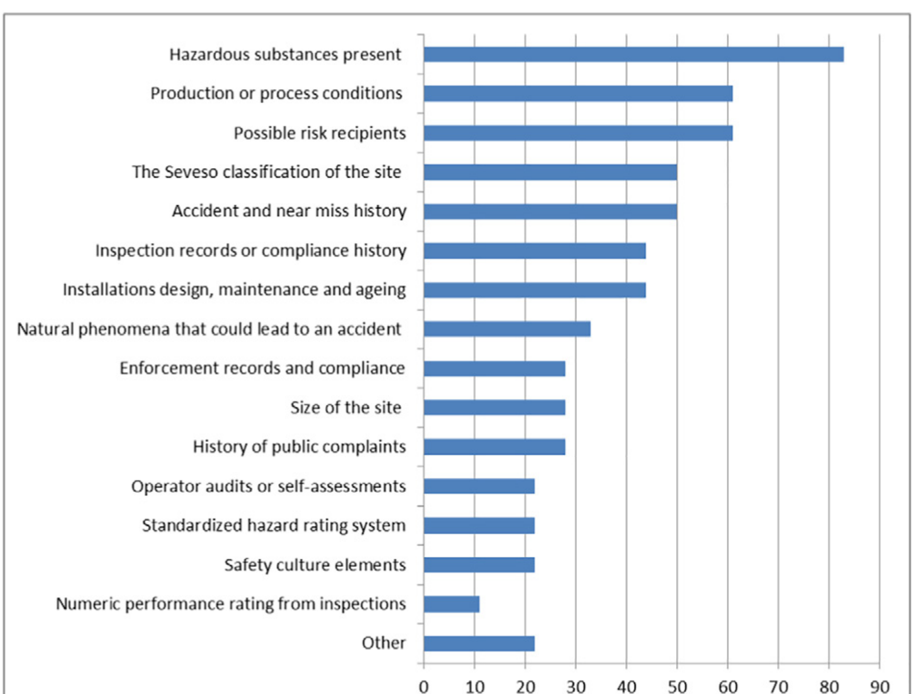

Fig. 6. Variables used to calculate hazard ratings in 18 EU/EEA and UNECE TEIA by percentage of countries using them [15].

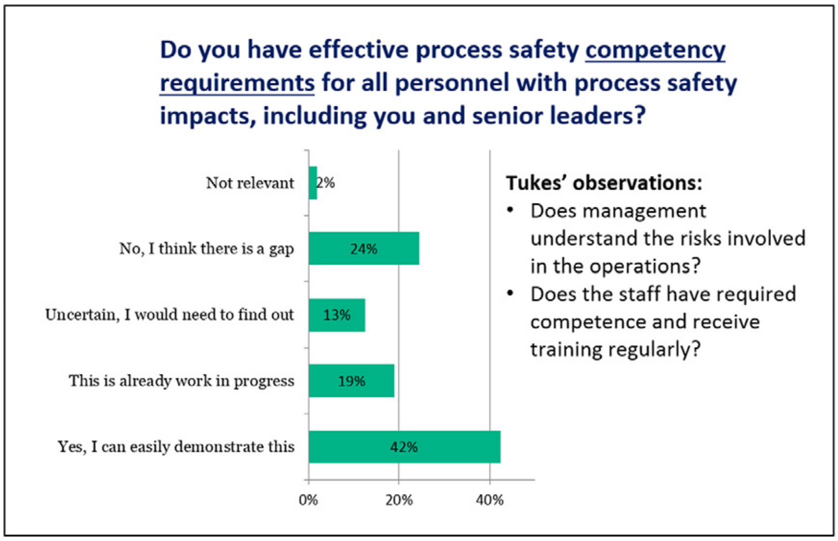

Fig. 7. Example of results from Finnish survey on corporate governance [18].

It is possible also to quantify risk governance results into risk governance indices. To enhance the use of survey results, the EC-JRC developed quantitative indices to measure existing capacity and limitations of a country in achieving certain milestones in implementing a chemical accident risk reduction programme [20] (See Fig. 8). Numeric results for these indices were developed from survey questions and weighted to achieve final results. These numbers could be used to benchmark the current state of risk governance in government and to measure progress in improving the programme at various intervals following implementation of a capacity building strategy. The EC-JRC is currently working on Seveso performance tracking index based to benchmark a country's progress in implementing or aligning its government programmes with the EU Seveso Directive.

3.12. Case studies of major chemical accidents and disasters

Major investigation reports and studies of recent chemical disasters or accident trends also can give substantial insights into risk drivers and vulnerabilities associated with particular types of hazardous industries. Findings from investigations of major catastrophes, such as the Longford gas plant explosion (Australia, 1998) and the Enschede fireworks disaster (Netherlands, 2000) and many others are particularly noted for the perspective they offer on the role that safety culture and management attitudes of organisations can play in augmenting or minimizing chemical accident risk. These observations can be valuable input to industry and government on evaluating risks associated with the operations they oversee. There is information for process safety experts from diverse incidents as the Fukushima and the Challenger space shuttle disasters. Some trends identified in recent years on the basis of chemical accident investigations are listed in Table 2.

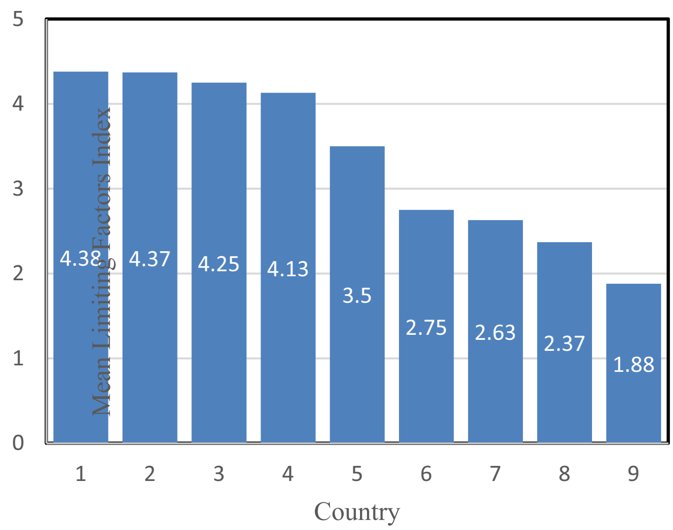

Fig. 8. Limiting Factors Index (EC-JRC survey of nine EU Neighbourhood Countries) [20].

Table 2
Examples of trending topics surrounding new and complex risk factors in process safety today [21].

Trending topics	Description
Ageing of capital and human resources	Ageing of equipment, people, procedures, and technologies
System complexity	An unanticipated interaction of multiple failures in a complex system
Increase in outsourcing of personnel	Increasing engagement of third party personnel to work in critical functions such as maintenance and operations functions
Increased automation of process controls	Expanded use of computer technology and software engineering to control processes
New products, processes and market demands	Renewable energies, biofuels, and liquefied natural gas (LNG) industries are all examples of sectors in a growth phase where experience on some risk aspects are limited
Organisational management, including organisational change	Change affecting the entire site or company, e.g., change of ownership, re-organisation, and downsizing of staff
Risk governance	The government's performance in implementing and enforcing relevant laws
Corporate leadership	The ability of the upper management to establish and enforce robust process safety management company-wide
Safety culture	The attitude, beliefs, perceptions and values that employees share in relation to safety in the workplace.
The Internet of Things	The network of physical devices, vehicles, appliances and other items that can connect across a local Internet and exchange data

4. Conclusions

There is still a long way to go in establishing appropriate measures and collecting data that could be used to assess global progress in reducing risk from chemical accidents. It will require substantial reflection and coordination across countries and industries at international level to identify measures that can be applied in a broad range of countries with varying levels of industrial activity, varied institutional arrangements and practices for governing industrial risk, and cultural and social differences. Assessment of chemical accident risk at global level is likely to be achieved through a combination of data collection measures, with both government and industry making contributions. Data collection should be customised to reflect local circumstances and different expectations for countries with different levels of risk governance. Countries with more competence and experience would be expected to have more sophisticated data collection measures in place for assessing progress, as is already the case in several OECD countries. Over time as other countries achieve higher levels of expertise in their risk reduction efforts, they can also begin to implement more advanced assessment strategies.

Chemical accident risk can often be underestimated by countries when there is low visibility for chemical accidents. In some countries, such incidents are not reported with consistency due to any number of reasons, including low public awareness, lack of government attention, and geographic limitation of impacts. This is a particular danger for developed countries that see industrial incidents as a normal event and do not notice that their occurrence reveals the existence of hidden and deeper problems. The complexity of improving risk management can be a daunting task for emerging economies and systematic measurement can help them prioritise and target problematic areas.

Moreover, it is important that assessment of chemical accident risk be inclusive of all relevant industry sectors. The tendency of government to regulate by source type and size can result in particular attention to the performance of some companies and industries with these characteristics. At the same time, there may be far less awareness of companies and industries that do not meet these criteria, despite equal or greater levels of hazard exposure (to populations, to environmental and economic resources). In this regard, assessment of risks needs to cover all types of hazard sources (fixed facilities, transport, pipelines, and offshore facilities) as well as non-chemicals industries using dangerous substances that may require certain level of hazard control.

Strengthening data collection on past accidents should also be a priority. Data on past chemical incidents is fundamental to global and national assessment of chemical accident risk. However, these data are only a starting point for making a more robust assessment. By itself, aggregate accident data can hide significant gaps and challenges in risk reduction efforts associated with particular economic sectors and technological and social change. Moreover, the low frequency of severe chemical accidents means that incident data associated with any one country or industry, or even across several countries and sites, is not a reliable indicator of underlying risk, particularly in locations where a certain level of risk control has already been achieved.

Fortunately, industry and governments around the world, as well as some international organisations, are actively working to improve measures for providing feedback on their risk reduction performance. Some dialogue has already started on possible improvements to current data collection mechanisms in the EU and is ongoing in many industrial countries. Further dialogue at international level might be necessary to consolidate knowledge and experience, make recommendations to countries that do not yet have assessment methods in place, and to begin testing some ideas.

The last decade in particular has seen the emergence of innovative ideas that can form the basis for international recommendations for data collection and the development of implementation models. It will take some years to establish, test and implement these recommendations so that more countries are encouraged to establish and implement their own assessment strategies. However, there are many countries already leading the way that could perhaps, by example, hasten the process.

It is imperative to have an assessment of risk reduction performance so that politicians continue to give chemical accident risks attention. There is ample motivation for all stakeholders to engage in a process to develop more robust assessment measures for tracking chemical accident risk reduction efforts. It is hoped that this paper provides a rich overview of opportunities and resources for further dialogue on this issue at national and international level and in industry.

Declaration of competing interest

None.

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