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The impact of nature on chemical industrial facilities: dealing with challenges for creating resilient chemical industrial parks.

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Abstract

In this paper, a conceptual framework is developed to improve NaTech safety in the chemical industry. The concept is called EPIC, indicating that emphasis should be put on Education, learning and training, Proactive risk minimization and safety innovation, Intensified informed inspection and analysis, and Cooperation and transparency. Concrete initiatives addressing NaTech for every domain of the EPIC conceptual framework are given. The innovativeness of the EPIC framework resides in the potential of the simultaneous application of initiatives within the four areas of improvement (E, P, I, and C) to make chemical clusters much more resilient with respect to nature-related disasters. As such, the proposed EPIC framework may lead to a much-needed revolution of NaTech safety in the chemical industry.

Keywords: NaTech safety, chemical industrial facility, chemical clusters

1. Introduction

Chemical plants are attributed with large inventories of hazardous materials whose release could result in catastrophic events. The proximity of chemical plants to residential areas and transportation networks makes the potential consequences of such undesired releases even more catastrophic. The ever-increasing complexity and interdependencies of design and operational parameters in the chemical industry, exacerbate the vulnerability of these industrial activities and the severity and the extent of potential consequences, e.g., via cascading effects. For example, the emergence of chemical clusters has raised the concern of external (cross-boundary) domino effects in addition to notorious internal (within the premises of a single plant) domino effects (Reniers and Cozzani, 2013).

As opposed to technica or security accidents or incidents in chemical plants, which are matters of random failures (equipment or human) or malicious acts, respectively, those triggered by natural hazards – also known as NaTech events (Natural events triggering a technological scenario, e.g. damage due to flood water of oil storage tanks and release of their content, earthquake damage of storage tanks causing LPG release resulting in fires and explosions, etc.) – could result in more severe consequeces (Showalter & Myre 1994, Rasmussen 1995, Young et al. 2004, Krausmann et al., 2017). This is mainly due to the high likelihood of multiple simultaneous damage to process units and release of hazardous substances, as in the event of the 1999 Izmit earthquake in Turkey (Steinberg and Cruz, 2004), or extensive spread of chemical substances and catastrophic environmental pollution, as in the case of Hurricane Harvey (2017) in the U.S. (CNBC, 2017).

NaTech accidents modeling and risk assessment are challenging though their impacts are felt widely, and it is necessary to include them in chemical plant's safety assessment and management. The challenge arises as, from one hand, the magnitude and frequency of natural disasters such as earthquakes and floods are difficult to predict (aleatory uncertainty), and from the other hand assessing the impact of natural disasters on process units is highly difficult mostly due to lack of data and our incomplete knowledge of failure modes (epistemic uncertainty)

The threats deriving from NaTech scenarios have long been recognized and investigated in chemical and process plants (Young et al., 2004; Godoy, 2007; Cruz and Okada, 2008; Antonioni et al., 2009; Cozzani et al., 2010; Krausmann et al., 2011; Cozzani et al., 2014; Marzo et al., 2015, Krasumann et al., 2017). Accordingly, many techniques have been developed for quantitative risk assessment and management of NaTech events triggered by floods (Haptmanns, 2010; Landucci et al., 2012; Antonioni et al., 2015; Khakzad and van Gelder, 2018; Kameshwar and Padgett, 2018), by lightning (Necci et al., 2013; Necci et al., 2016; Wei et al., 2018), by tsunami (Mebarki et al., 2016; Araki et al., 2017; Nishino and Imazu, 2018), by earthquakes (Salzano et al., 2003; Fabbrocino et al., 2005; Antonioni et al., 2007; Campedel et al., 2008) and by wildfires (Khakzad et al., 2018) were developed.

Nevertheless, the attention devoted to Natech-related safety assessment and management in the form of regulations, directives, and standards has been quite low till present. In Europe, the well-known Seveso Directive (Directive 2012/18/EU) has recently mandated the companies falling under the obligations of the Directive to consider the possible impact of natural disasters (with an explicit mention of earthquake and flood) in safety reports. The recent NaTech events in chemical plants in the Houston area in Texas, US, due to the Hurricane Harvey in August 2017, have clearly demonstrated the vulnerability of chemical plants to natural hazards. Recent examples of NaTech events impacting on the chemical industry should raise industry awareness concerning the severity of NaTech threat and the need for taking effective measures not only to reduce the vulnerability of chemical plants but also to reduce the potential consequences of possible NaTech events in chemical plants.

2. Problem statement

Although the frequency of Natech events related to chemical facilities is rather low (between 3% and 5% of reported industrial accidents according to Krausmann et al., 2011), the risk of a natural event for the integrity of industrial chemical and process plants and clusters should not be underestimated by operators and regulators due to the severity of the consequences of such scenarios.

Substantial release of petroleum products occurred due to Hurricane Katrina in 2005 in the United States, and this release is actually categorized as the second largest oil spill disaster after the BP spill in the Gulf of Mexico in 2010 (Sturgis, 2015). This release, as well as fires in a refinery in Turkey due to the Izmit earthquake in 1999, as mentioned before, are just some examples of NaTech accidents. Aside from direct damage caused by NaTech accidents, simultaneous damage to other infrastructures such as communication and power grids, pipelines, and transportation infrastucture, hampers emergency response procedures, thus aggravating the extent and severity of consequences (Campedel, 2008, Krausmann and Mushtaq, 2008).

In August 2017, the Hurricane Harvey in the U.S. caused damage to storage tanks in refineries and petrochemical plants, leading to a substantial release of pollutants[1]. Aside from direct structural damage to industrial plants, the power outage in a chemical facility coupled with the damage of backup generators, made some extremely reactive and unstable chemicals (organic peroxides) – which must be kept refrigerated – decompose. Several explosions affected the site, and the gaseous plume of decomposition products caused injuries among first responders (the guardian, 2017).

The structural damage caused by natural events at industrial plants, however, does not compare with the environmental damage and revenue losses due to interruption in production and supply chain: the Hurricane Harvey forced oil refineries to shut down their operations in the wake of heavy rainfall and flooding, leading to at least a loss of more than 1 million barrels per day in refining capacity

[1] The accurate extent of damage to industrial plants due to the Hurricanes Harvey and Irma is still under investigation. and thus not yet known.

(CNBC, 2017). Besides, as of September 12, 2017, Hurricane Harvey has been estimated to have caused 4.6 million pounds of chemicals to be released (www.businessinsider.nl).

Investigating the available industrial accidents databases in Europe and the US, Campedel (2008) and Cozzani et al., (2010) identified 272 records of flood-related NaTech events (1960-2007) and 78 records of seismic-related NaTech events (1930-2007) in the chemical and process industries. Figure 1 shows the type of industrial facilities impacted by flood (Cozzani et al., 2010).

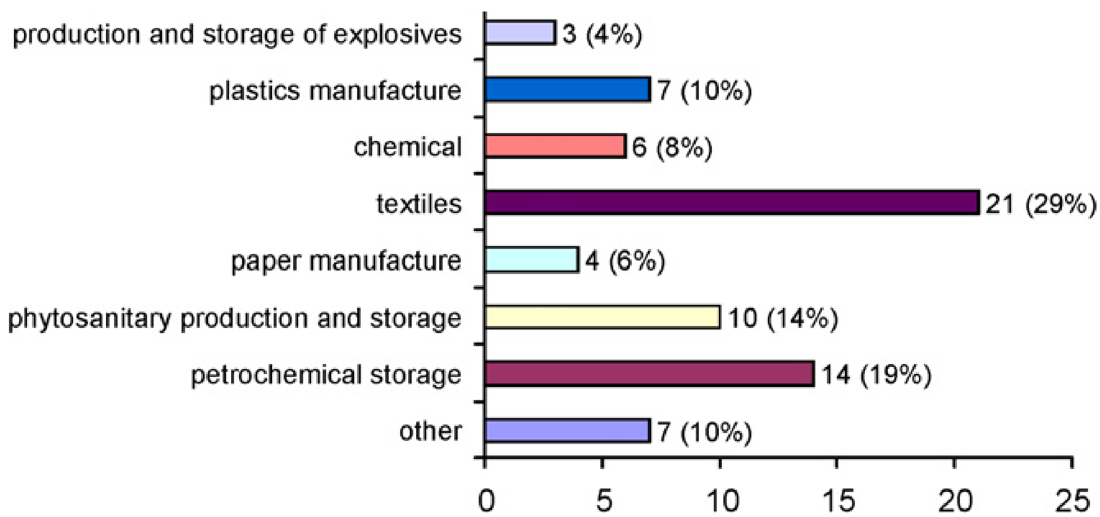

Figure 1. Types of industrial plants impacted by floods (Cozzani et al., 2010)

Due to the ever-increasing growth in the numbers and sizes of industrial facilities and the subsequent prolonging interface with nature from one hand, and the anticipated increase in the frequency and severity of climatic disasters on the other hand (e.g., floods, hurricanes, forest fires, etc.), an increasing trend has been foreseen for the occurrence of NaTech events (Parry et al., 2007). Despite the emerging risk of NaTech events, specific Quantitative Risk Assessment (QRA) studies have been very few (for an overview see Cozzani et al., 2014; Cozzani and Salzano, 2017). This has been partly due to the lack of explicit legislation and transparent guidelines to include the risk of NaTech events in safety reports required by control authorities (Krausmann and Baranzini, 2012) and partly owing to the scarcity of high-resolution historical and experimental data (Campedel, 2008; Cozzani et al., 2010).

As already indicated, in Europe, only the last update of Seveso Directive (Directive 2012/18/EU, 2012) has recently mandated the member states to consider the probability of natural disasters in the risk assessment of major accident scenarios when preparing the safety reports (Article 10), with an explicit mention of floods and earthquakes in the Annex II. The most of European countries that consider NaTech events have likewise limited their programmes to a few natural hazards (Krausmann and Baranzini, 2012). Besides a lack of efficient regulations, factors such as loose supervision of law enforcement (if any) on the preparation for NaTech disasters, handling such risks by means of the same approaches as regular operational safety, lack of communication and sharing of information and knowledge within and between chemical facilities, application of outdated risk assessment techniques and insufficient knowledge of state-of-the-art QRA methodologies are among those which lead to the observation of inadequate (or inefficiency of) NaTech risk assessment and management in chemical industrial parks, not only in developing but also in developed countries. In the following, a number of challenges and new trends in the domain of NaTech safety for chemical plants, will be discussed in more detail.

3. Challenges of chemical plant safety with respect to NaTech Hazards

3.1. The role of education and ethics

Education on chemical safety and security (CSS) with "chemical ethics" (amongst other topics concerning the environment) as groundwork is a possible instructional method that may prove essential to the successful implementation of NaTech risk mitigation measures, and improve NaTech risk management in chemical plants. When a NaTech event takes place, there is not only the potential for human fatalities, but also, and with higher likelihood, the possibility of severe consequences on the environment is present.

However, only in recent years the awareness of the specificity of NaTech accidents became evident. Thus, no consolidated education model is available. Time to time professional courses on safety address NaTech as one of the topics: e.g. in the framework of FP7 project iNTeg-Risk, a specific module six principal units:

- Introduction to the Assessment of Major Accidents in Industrial Plants
- Assessment of Industrial Risk Induced by Natural Events (NaTech)
- Quantitative Assessment of Domino Effect
- Introduction to QRA
- QRA of NaTech and Domino Accidents
- Case-Studies and Use of Risk Results …

It is evident that the course was conceived to clearly remark the complex characteristics and the potential wide impact of Natech scenarios, linking NaTech to domino effects and cascading events. However, in traditional approaches, the courses address separately natural and entropic risk, and pay limited attention to their interactions as is the case in NaTech scenarios and other types of cascading events. Education and training on NaTech events should therefore form a regular part in process safety management within a chemical facility.

3.2. Consequence assessment: conventional versus NaTech approaches

Considering a NaTech risk assessment in form of a Bow-tie diagram in Figure 2, where the occurrence of a NaTech event is situated in the center (e.g., release of gasoline from a storage tank) with the causes (flood, earthquake, etc.) and prevention measures (anchorage, shell stiffener, etc.) on the left-hand side and the consequences (fires, toxic dispersions, casualty, environmental pollution, etc.) and mitigation measures (dike, fire protection system, etc.) on the right-hand side, a majority of the previous studies in the field of NaTech risk assessment were devoted to the left-hand side, that is on the assessment of the likelihood of the release (see Cozzani et al., 2014, and Cozzani and Salzano, 2017, for a comprehensive review of the state-of-the-art). Limited efforts were dedicated to-date to the specific assessment of post-release event trees in NaTech conditions. Compared to 'conventional' safety-related events, it is obvious that Natech events are expected to impact far larger areas, with consequences that may be far more severe than those of a single technological scenario or of the natural event without considering the cascading technological scenarios. For instance, in the event of floods, an accurate consequence assessment would require accurate estimates of the amount of the waterborne released chemicals, and their behaviour in the flood water after the release. This, in turn, demands for sophisticated numerical models, e.g. to calculate the fate of waterborne oil spills or of soluble chemical substances as chlorine (Krausmann et al, 2017). Despite many studies devoted to environmental risk assessment in the event of natural disasters such as floods (Tilotta et al., 2003; Arrighi et al., 2018), specific assessments in the domain of NaTech consequence assessment, to the authors' best knowledge, are lacking.

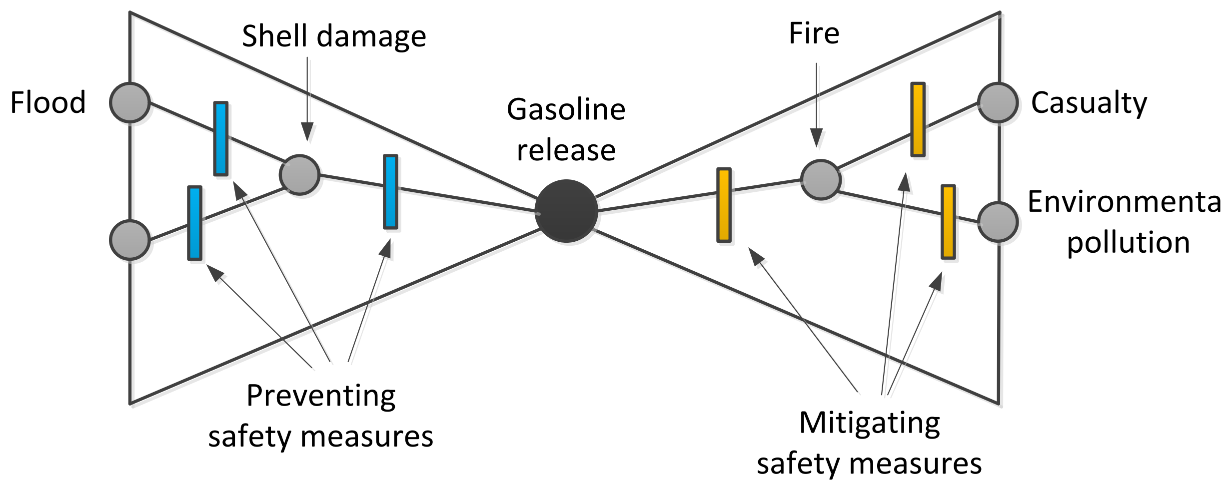

Figure 2. The bow-tie concept for a gasoline storage tank subject to natural disasters.

3.3. Likelihood and frequency of Natech events

One of the most challenging parameters to estimate in NaTech risk assessment is the likelihood of the devastating consequences of a natural disaster. A wide variety of factors should be taken into consideration in predicting the severity of the devastation and its likelihood. However, it should be remarked that NaTech events are triggered by the impact of natural disasters on industrial structures (both buildings and equipment items as storage tanks or process vessels). Thus, the analysis of the likelihood of such events can be divided in two parts: the assessment of the likelihood of natural disasters with a given intensity, and the conditional probability of damage of industrial structures impacted by the natural events. The separate application of the above mentioned techniques to this specific framework provided useful results.

When considering the characterization of natural hazards, relevant parameters are, amongst others, (i) the general history of threatening events and events in similar industries – locally, regionally, nationaly and internationally – (ii) site-specific record of natural events at the site, (iii) potential severity of the natural event at the site. In recent years, important results were obtained in the characterization of natural hazards, and maps providing expected severities and times of return are now available or can be calculated.

However, when the specificity of Natech scenarios is considered, the issue of data scarcity arising from the rarity of NaTech events impacting chemical facilities limits the application of conventional frequentistic approaches to likelihood estimation. In recent years, a number of techniques have been developed to make use of precursor data (indirectly relevant data) in reasoning and risk assessment of rare events where the amount of directly relevant data is not worthwhile. Application of such precursor-based methodologies to, among others, NaTech data may be employed to infer NaTech risks. As an alternative, specific models may be applied to the assessment of the conditional probability of equipment failure when impacted by natural events. Vulnerability models where developed and are now available for a number of equipment and natural events as eartquake, flood and lightning (e.g. see Campedel et al., 2008; Landucci et al., 2012; Landucci et al., 2014: Necci et al. 2013).

3.4. Inherently safer design techniques

The concept of Inherently Safety or Inherently Safer Design (ISD) was first introduced by Kletz (1976) following the Flixborough disaster in the UK in 1974. ISD is not a tool but a mental disposition which is aimed at eliminating the hazard instead of trying to control it or to mitigate the consequences. Kletz' famous quote "What you don't have, can't leak" has been interpreted via five themes: (i) minimization, (ii) substitution of hazardous materials and/or processes with less hazardous ones, (iii) moderation of process parameters such as temperature and pressure (iv) simplification of processes, and lately (v) moderation in terms of limitation of effects, via, for example, separation distances between critical units (e.g., storage area and control rooms).

The benefits of ISD in NaTech risk assessment can be many folded. For instance, by minimizing or substituting hazardous materials, not only the likelihood of devastation of chemical clusters is diminished but also the extent and severity of consequences would be minor in such circumstances.

Besides, through simplification of processes (e.g., neat and easy monitoring pipelines and valves), a release of chemicals is much likelier to be fully understood and (thus) followed by timely preventive and controlling measures when possible. Similar beneficial attributes can be gained from limitation of effects where a loss of containment and possible ensuing fire or explosion is less likely to escalate to secondary fire or explosions in neighboring units, initiating a domino effect.

Nevertheless, the context of NaTech requires a specific framework to be introduced, since inherent safety concepts may be extended as well to the design of the structural elements that may be impacted by the natural disaster.

3.5. Land-use planning

Similar to ISD, land use planning (LUP) is a non-structural safety measure aimed at mitigating offsite consequences of major accidents by protecting people from exposure to dangerous doses generated by fire (heat radiation), explosion (overpressure), and especially dispersion of toxic materials (toxicity). In LUP, the land around either a major hazard installation such as a chemical facility or hazardous pipeline such as an oil & gas pipeline is divided to zones usually based on the severity of potential consequences of possible accident scenarios (consequence-based LUP) or amounts of individual or societal risks (risk-based LUP).

Figure 3 exemplifies a risk-based LUP practiced by HSE in UK where the boundaries of inner zone (IZ), middle zone (MZ), and outer zone (OZ) are determined with individual risks (annual probability of death) corresponding to 1.0 E-05, 1.0 E-06, and 3.0 E-07, respectively. Based on the amount of individual risk (probability of death as a result of exposure to lethal dose) and vulnerability of users (manufacturer employees, primary schoolers, etc.) there can be advice against (AA) or no advice against (NAA) activities/developments in each zone (Table 1). This way, LUP can effectively alleviate the extent and severity of consequences at least in terms of loss of lives and environmental damages (in case the environment itself is considered in LUP as a vulnerable user).

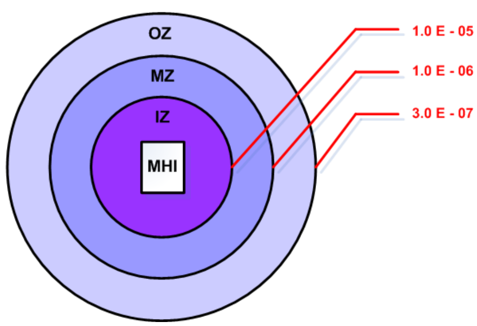

Figure 3. Risk-based land use planning (HSE, UK). The land around a Major Hazard Installation (MHI) such as a chemical plant is devided into three zones, that is, Outer Zone (OZ), Middle Zone (MZ), and Inner Zone (IZ) based on the respective amounts of individual risk (annual probability of death).

Table 1. Land use development based on the individual risk and user vulnerability (HSE, UK)

Type of land use development	Zones in Figure 6		
	IZ	MZ	OZ

Factories with limited number of employees	NAA	NAA	NAA
Residential houses with limited number of residents	AA	NAA	NAA
Primary schools and nurseries	AA	AA	NAA
Airports, football stadiums, large hospitals	AA	AA	AA

The majority of previous studies over the past two decades as to the role of LUP in safety assessment and (safety) risk-based design/decision-making of chemical facilities was inspired by the EU Council Directive 96/82/EC, a.k.a Seveso Directive II. Articles 12 of the Seveso II explicitly mandates the EU Member States to consider LUP for the limitation of major hazards consequences to man and environment. Article 12 is mainly devoted to (i) siting of new installations, (ii) modification of existing installations, and (iii) land developments in the vicinity of existing installations, particularly those developments which would increase either the population at risk or the severity of the risk. In other words, in general it may not be applied to an existing installation unless there are any internal modifications to the plant or external land developments in the vicinity of the plant. However, to the best knowledge of the authors, the inclusion of NaTech risks in LUP has not been considered as yet, which otherwise can remarkably reduce the severity of offsite consequence of such nature-related events and thus lessen the level of devastation of a chemical industrial park. Also, LUP can be used on the reverse side, avoiding the installation of hazardous facilities in areas prone to natural disasters as earthquakes or floods.

4. Evolutionary approaches to improve safety in chemical industrial parks

The number of safety-related tasks in any organization is huge, so are the responsibilities accompanying the decisions and choices that have to be made (see also Meyer and Reniers, 2016). Well-known (technical) aspects of safety assessment and management in companies, that is, hazard identification, scenario modeling, and risk analysis and assessment, are only one part of the larger domain of dealing with risks undertaken by company safety managers. Other elements include, but are not limited to, safety training and education, training-on-the-job, management by walking around, emergency response and planning, business continuity planning, ethical aspects of safety, reliability engineering, learning from incidents, risk communication, risk perception, psycho-social aspects of risk, economic aspects of safety, risk governance, and many more. Safety managers nowadays realize that this set represents their package of responsibilities. From a rather very technical approach, safety management has expanded towards an approach encompassing all these other domains, to a lesser or higher extent.

Furthermore, the scientific background and the disciplines needed to tackle the different domains and items in the risk management set are ever more diverse. Safety- and risk management are no longer the exclusive terrain of engineers, physicians, and safety scientists; in fact, sciences such as psychology, sociology, pure mathematics, chemistry and physics, philosophy, economics, communication, business and management, criminology, and law are also effectively involved in safety improvement these days.

Employing the well-known bow-tie concept (Figure 2) to explain the evolutionary trends taking place in safety improvement in the chemical industry, three areas may be discerned: the proactive phase (pre-incident), the incident phase, and the reactive phase (post-incident). In the proactive phase, a variety of trends can be observed and discussed (see also Reniers and Khakzad, 2017). The first trend is that there is ever more cooperation between companies, however mainly limited to an operational level and mostly concerning reactive issues such as accident investigation and evacuation exercises. More collaboration among companies, academia and authorities can also be noticed. The second trend concerns making risk assessments less static and more dynamic (Paltrinieri and Khan, 2016). Dynamic risk analyses include advanced mathematical-based techniques being developed in the academia including Markov chains (see e.g. Shu and Zhao, 2014), Event sequence diagrams, Petri-nets (see e.g. Zhou et al, 2016 and Zhou & Reniers, 2016a,b,c), and Bayesian Networks (see e.g. Khakzad, 2015).

Furthermore, operational economics, including cost-benefit analysis and cost-effectiveness analysis, are improved and employed with an increasing trend (see e.g. Reniers and Sörensen, 2013; Reniers and Brijs, 2014; Reniers and Van Erp, 2016). Some specialized topics have also been explored, introduced and developed in chemical corporations, such as security risk analyses (see e.g. Reniers et al., 2012, 2014; Reniers & Audenaert, 2014; Landucci et al, 2015), performance management science (see e.g. Swuste et al, 2016), mental models (see e.g. Blokland & Reniers, 2017) and moral or ethical principles for calculating risks. The attention for systemic risks, whereby one looks at the whole system rather than (analytically) looking at its parts, leads to the taking of safety barriers at a systemic level (see e.g. Reniers, 2010, 2013). An example is that one looks at a whole chemical plant at once instead of merely considering its installations or equipment. Besides, a variety of scientific disciplines are employed to invent trans-disciplinary solutions. All kinds of safety apps can further be expected to lead to optimized communication and perhaps much better safety decision-making. Innovation with respect to the so-called 'safety culture', via, for example, High Reliability Organization principles or newly developed leadership styles such as Total Respect Management (Blokland and Reniers, 2017) or decision-making informed by game-theory (Reniers & Pavlova, 2013; Zhang & Reniers,

2016) are also being elaborated. These pro-active research trends are not aimed at NaTech-related safety.

Also in the incident phase some evolutionary trends can be observed. Real-time data and big data, as well as all progress in communication devices and possibilities have led to better and more objective risk assessments and decisions, as well as regulations such as Land-use Planning. Large-scale simulation exercises of disasters are made more real while serious games to exercise incident-phase decisions and tasks are elaborated. Collaboration between different actors in the incident phase is also improved with more involvement from the public and the authorities. None of these trends are specifically aimed at improving capabilities and understanding in case of NaTech-related disaster. This is of particular relevance, since the correct response, also concerning the equipment that needs to be used and the response plan, may be extremely different when responding to a natural event or to a NaTech scenario. Specific emergency plans and specific emergency response resources and measures are needed when dealing with NaTech.

During the aftermath of an incident, an important evolutionary trend of improvement concerns better collaboration among rescue workers, fire-fighters, industrial practitioners, medical services, logistics services, communication experts, and academics. Moreover, the use of innovative technology (e.g., drones), certain human aspects (e.g., trauma-psychological aspects), and organizational structures to deal with problems in a post-incident phase are trends that cannot be disregarded. Finally, NaTech scenarios may need important intermediate steps, as environmental decontamination, before recovery operations can be started. Reactive research being carried out can also be used in the case of NaTech events.

In summary, with respect to NaTech safety, progress is currently made only in the reactive phase. The incident and certainly the before-incident phases are, however, less focused upon in current time, probably due to the relative novelty of the NaTech topic in the chemical industry.

5. Solution to challenges for NaTech risks: the 'EPIC' concept

While Section 3 provided the challenges for advancing NaTech safety with respect to chemical facilities, Section 4 illustrated the current trends which can be discerned in current academic research and industrial practice with respect to safety. However, these trends represent thinking 'within the box', and are usually 'more of the same concept/approach' or, at best, incremental improvements and optimization of existing technology, management practices, organizational arrangements, and human factors. To truly advance NaTech safety within the chemical industry, we need to think 'out of the box'.

We believe that this 'out of the box' thinking can be represented by the 'EPIC' acronym. EPIC concerns four very important fields where revolutionary progress is needed (see also Reniers & Khakzad, 2017):

- **E**ducation, learning, and training
- **P**roactive risk minimization and safety innovation
- **I**ntensified informed inspection and analysis
- **C**ooperation and transparency

At first sight, these fields represent well-known recipes for improving operational safety in any industry whereas they are nothing new. However, one should realize that the combination of these domains within the field of NaTech safety could indeed lead to major improvement of the resilience of chemical plants and clusters by radically innovative routes. The required innovation can be exemplified by a number of concrete ideas, which can only be realized if current mentality of practitioners, academics and authorities changes.

*5.1. **E**ducation, learning, and training*

One not only needs to learn from near misses and incidents but also from safety models, theories and knowledge in general. Here layes also a task for society: there should be courses on 'dealing with risk and uncertainty', or 'operational safety', starting from primary school education. If people get familiar with safety from very early ages, they can learn much more in higher education, and eventually focussed on NaTech safety for instance for chemical engineers. In this regard, the following concrete innovations can be thought of. For instance, knowledge management systems (a.o. for NaTech safety issues) need to be elaborated and should be present in every chemical plant. There should also be training sessions on NaTech safety. In such sessions, it can be recommended that plant safety managers and safety inspection services are jointly present. From a scientific viewpoint, safety learning should be supported by adequate and scientifically validated performance management indicators, with eye for NaTech safety. More generally, lessons related to basic knowledge of valuing and prioritizing safety should be taught to children in primary schools, so that they learn the safety basics and can learn much more in a later stadium of life. Subsequently, risk management and risk-based decision making should be taught at high schools and universities, either as a separate course, or within existing courses. In the same reasoning, inherent safety principles should be taught to all chemists, chemical engineers and industrial engineers, and be considered essential in the educational programs.

In case of Natech events, it is also very important that education and training is aimed at different disciplines efficiently working together and communicating effectively and promptly, since single-discipline process safety experts are not necessarily aware of the characterization of various natural event phenomena, the way that they unfold, and their protection. In particular, sufficient knowledge on natural hazards needs to be provided to company operational and safety managers. This is not usually in the background of personnel involved in the management and operation of chemical clusters. To this end, setting up specific training programmes and developing and carrying out large-scale exercises for creating and training the needed multidisciplinary approaches (including natural hazard mapping, communication technology and practices) for Natech events is recommended. Five different players usually deal with emergency response: (i) firefighters, (ii) police, (iii) medical responders, (iv) providers of materials and logistics, and (v) the people occupied with providing the right information, e.g. on internet, social media, etc. These players need to be educated and trained specifically for the case of Natech events. They should be trained to behave and respond to the specific circumstances occurring in the case of Natech scenarios, which are not necessarily similar to those occurring in the case of major accidents occurring during normal site operation. A long-term oriented plan for emergency management and –preparedness in chemical industrial parks, linked to educational needs, should be developed to this end.

5.2. ***P****roactive risk minimization and Safety innovation*

Remarkable innovations in the field of quantitative risk analysis (QRA) as a tool to improve safety, design, licensing, and operational processes were achieved. The improvement of methods for uncertainty handling and, more importantly, validation and verification of QRA results would contribute to make even more valuable such approach. This applies also to the field of NaTech safety for chemical plants. Thus, one of the main issues as for safety innovation could be consolidating techniques to verify and validate NaTech risk analysis in parallel with improving techniques for safety improvement and uncertainty handling. It is thus crucial to investigate which theoretical views on validity and validation of QRA can be found, which features of QRA are useful to validate, and which frameworks can be proposed for this purpose, what kinds of claims are made about QRA, and what evidence is available for QRA being valid for the stated purposes.

During the past decade, the attempts in the field of *dynamic* risk assessment have been made to address factors such as dynamic procedures for atypical scenario identification (including black swan and grey swan events), dynamic hazard identification (as a substitute for conventional static techniques such as FMEA, HAZOP, etc.), reactive and proactive approaches for probability updating using leading and lagging risk indicators, which in turn would result in a more effective uncertainty modeling, dynamic consequence analysis so as to consider temporal variations of contributing parameters such as vulnerability, economic conditions, etc., and dynamic risk management (for a detailed discussion see Paltrinieri and Khan, 2016). It is evident that dynamic risk assessment for NaTech poses great challenges but will lead to real-time insights in NaTech safety of chemical industrial parks.

Some innovations that, if applied together, would make this evolutionary trend a true revolutionary field, can be suggested. One can for instance think of the use of big data and the Internet of Things to innovate risk knowledge and safety decision-making within chemical plants and chemical clusters for NaTech events. In particular, data integration and data analytics may allow, in perspective, to integrate data on natural and technological risk, that currently are still separately handled.

Analogously, there should be investments in the development and on-site application of dynamic risk assessment techniques, in order to advance real-time knowledge and decision-making for NaTech events, in particular addressing decision making based on early warnings. Another line of research that should be invested in, is performance management science and knowledge and know-how about safety performance indicators with respect to NaTech safety, to understand which indicators are more significant and also to know which indicators are not usueful and can be considered as 'dead weight' for the company. Such performance management studies require large-scale longitudinal studies and thus represent not only financial investments but also (and even more so) time investments. Furthermore, 'serious games' for a large variety of NaTech event scenarios can be developed and employed for learning and exercising in chemical plants. Finally, science should be build up with respect to leadership, required mental models of employees, and the impact on safety. This validated knowledge should then be implemented in chemical plants and industrial parks.

More concrete examples of practical approaches can be mentioned: the development of all-hazard databases including Natech scenarios to allow decision making for prevention and mitigation, early warning systems and the risk-based elaboration of their output to address decision making, use of drones for providing medical equipment and medical care in case of a NaTech event (such as a flooding, a landslide, an earthquake, etc.), the proactive setting up of robust communication lines that consider the specific features required to cope with NaTech scenarios, the development of software that can be applied to an area providing information for decision-makers to prioritize budgets for safety barriers and protection systems.

*5.3. **I**ntensified informed inspection and analysis*

Inspections and audits, be they company-related or authority-driven, should be more effective when it concerns NaTech safety. Often, inspections are not at all aimed at NaTech safety in case of chemical industrial activities. Besides operating plant personnel, inspectors and auditors should be well-educated and NaTech risk parameters should be assessed and inspected, in one go with operational safety inspections of installations.

Accordingly, the following innovative approaches can be introduced and elaborated in the chemical industry worldwide. A national, or if possible and even better, international, database to report all parameters related to potential NaTech events in chemical industrial sites can be established. Related to the database, a dissemination system where companies and authorities or inspection teams can learn from all NaTech incidents worldwide should be elaborated. Furthermore, an understanding between cluster safety council members and inspection services, to make inspections more efficient with respect to NaTech safety, needs to be developed. One of the tasks of auditors and inspectors is to assess and evaluate the plant emergency procedures in case of natural events.

Although to date no NaTech-specific inspections are carried out, in Europe, the implementation of Seveso-III Directive (Directive 2012/18/EU) requires the inclusion of NaTech scenarios in safety reports issued for the sites falling under the obligations of the Directive. Thus, during the regular inspections foreseen by the “Seveso” regulations, inspectors have now the possibility to check the compliance with NaTech risk assessment and the adequacy of NaTech scenarios considered within company policies for prevention and prepardeness. Several specific studies and pilot projects already considered the effect of NaTech scenarios for chemical clusters or extended industrial areas (e.g. see iNTeg-Risk, 2013).

*5.4. **C**ooperation and transparency*

Cooperation on a proactive and strategic level with the aim to enhance nature-related safety management, such as joint emergency management strategies and decision making tools, besides reactive and operational level cooperation such as joint evacuation drills, cannot be overestimated as an improvement way for NaTech safety. Some chemical industrial parks have already started working together so as to strategically improve horizontal logistics, the use of energy (or utilities in general), or environmental issues (e.g. waste streams); however, they usually fail to collaborate more intensively with respect to proactively and strategically enhancing safety, and this is certainly true in the specific domain of NaTech safety.

The following concrete innovative approaches can be considered. A multi-plant council or a cluster council should be established to tackle NaTech safety issues. Proactive strategic cooperation and improvement by setting up a 'cluster safety funding' budget for dealing with NaTech safety, could be fixed. A cluster early warning system for natural events that may trigger NaTech scenarios, as well as a cluster emergency planning matrix for the case of impending NaTech devastation, can be realized in the context of chemical industrial parks. Various forms of risks such as knock-on effects and cascading events, related or not with NaTech accidents, need to be taken into account in risk assessments for chemical parks. In brief, a cluster safety management system approach for NaTech risks need to be developed.

6. Conclusions and recommendations

We argue that NaTech safety still has a long way to go in the chemical and process industry, and that the field is still in its puberty, in industrial practice. New paths need to be walked on by academia and by industrial practitioners since the world has profoundly changed – and is still changing – in terms of climate change, interconnectedness of people, communication and social media, and technological progress (e.g. drone technology). All these societal changes urge chemical industrial parks to think of innovative and intelligent ways to tackle NaTech risks.

Operational safety insights and evolutionary safety management progress can indeed be used to steer basic NaTech safety progress, but more is needed. The challenges and trends that we discussed in this paper show that NaTech risk assessment and management in chemical plants can and should really take a leap forward in the near future, obviously preferably without the occurrence of major earthquakes and/or floods impacting chemical industrial sites in a horrible way.

Revolutionary progress in NaTech safety of chemical industrial facilities can be made by simultaneously focussing on four domains denoted by acronym 'EPIC': **E**ducation, learning and training; **P**roactive risk minimization and safety innovation; **I**ntensified informed inspection and analysis; and **C**ooperation and transparency. These fields together can truly and in a sustainable way change the NaTech safety landscape within the chemical and process industry.

Finally, better safety will also further reduce environmental risk and would give a new impetus in terms of sustainability of chemical industrial activities. In brief, bringing the EPIC concept into practice would bring the vision of resilient chemical industrial parks, encompassing the whole chain of activities of plant and cluster design, construction, commissioning, operation, and finally decommissioning, also in a sustainable sense.

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