



Reducing unknown risk: The safety engineers' new horizon

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ABSTRACT

A significant gap exists between accident scenarios as foreseen by company safety management systems and actual scenarios observed in major accidents.

The mere fact that this gap exists is pointing at flawed risk assessments, is leaving hazards unmitigated, threatening worker safety, putting the environment at risk and endangering company continuity. This scoping review gathers perspectives reported in scientific literature about how to address these problems.

Safety managers and regulators, attempting to reduce and eventually close this gap, not only encounter the pitfalls of poor safety studies, but also the acceptance of 'unknown risk' as a phenomenon, companies being numbed by inadequate process safety indicators, unsettled debates between paradigms on improving process safety, and inflexible recording systems in a dynamic industrial environment.

The immediacy of the stagnating long term downward major accident rate trend in the Netherlands underlines the need to address these pitfalls. A method to identify and systematically reduce unknown risks is proposed. The main conclusion is that safety management can never be ready with hazard identification and risk assessment.

1. Introduction

What lies beyond the border between known and unknown parts of the world around us is not merely a remote mystery. It affects us all in everyday life. We discover new things every day. Things outside our control happen to us every day. Accidents threaten our safety at work. We use the term "risk" to describe the product of probability and effect of an event that can cause harm to people and damage to plant and environment. The causes of frequent occupational accidents are usually rather well understood and countermeasures can be taken since they are known and available. This is not so in companies where complex processes and installations are running in order to store, mix and produce hazardous chemical substances (Galen and Bellamy, 2015). There, right in front of our eyes, a mysterious *unknown* shows itself through observed events during *major accidents* (EC, 2012) which do not consistently match with foreseen accident scenarios (Kleindorfer et al., 2003; Dort, 2016). This implies that a *scenario gap* exists. There are more scenarios than those which are being managed, and due to the phenomenon of *entropic risk*, the *dynamic features of risk* (Mol, 2003) and *emerging technology* (Kingston et al., 2016), new scenarios arise continuously. In other

words, this gap shows between all the risks which are actually present, either known or unknown, and the risks that are actually being managed. The presence of this gap points at an incomplete risk inventory, and at failing risk management (Hubbard, 2009). This notion is significant since major accidents pose a near to constant level of threat to society in the Netherlands and Belgium over the past decades (Swuste and Reniers, 2017; Reniers and Khakzad, 2017; Veld, 2015). After a preceding period of dropping accident rates, this 'plateau' indicates that major accident prevention and reduction activities fall short for as yet unexplained reasons and that further improvement of risk control is necessary (Le Coze, 2013). The authors contend that the *scenario gap* covers a significant part of these unexplained reasons.

In this study the authors explore "unknown risks" and propose a way to systematically deal with such risks. Rather than providing answers, the authors concentrate on questions generated by many paradigms and approaches in current safety science. This leads to an unconventional – narrative – structure of the findings, describing the path the authors followed. In the analysis section several examples are included, known to the general public, in order to explain the philosophical line of thinking. By means of a proposed scale and a range of identified process

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industry related unmitigated hazards (Lindhout and Reniers, 2017A), the authors construct a method to act on these not – or not fully mitigated hazards. Preliminary results of this work were presented at the 2019 Loss Prevention Conference (Lindhout, 2019A).

1.1. Problem definition

The mere presence of the scenario gap and associated unidentified hazards points at flawed risk assessments and, perhaps even more important, at flawed risk assessment approaches. The authors consider knowledge of paramount importance when controlling risks. A danger should be identified and sufficiently understood before it can be effectively dealt with as a controlled risk. Both company safety management and regulator activities need improvement on this point (Le Coze, 2013; Veld, 2015). Safety managers and regulators, attempting to reduce and eventually close this gap, encounter several pitfalls in safety management.

The *first* one is a poor safety study, generated by a company to establish its risk inventory and take appropriate safety measures. The resulting risk assessments can be incomplete for many reasons. General risk assessment practice has a focus on *worst case* scenarios. Choosing the rather unlikely scenario with the largest impact out of a group of similar but smaller impact scenario's as representative for all of them, ignores part of their variety. Hence such a choice can be baffling, hiding and obscuring the actual and more likely smaller accident risks (Dort, 2016; Kleindorfer et al., 2003). Companies measuring their safety performance can become a victim of the *McNamara fallacy* (Kingston-Howlett and Dien, 2017) which is associated with being numbed by inadequate process safety indicators. Companies simply get the wrong – usually too optimistic – impression of their efforts and of the effects their safety management system has on company safety.

A risk inventory can be incomplete thanks to a lack of 'risk appetite' (Gjerdrum and Peter, 2011), meaning that insufficient depth is achieved in the investigation of risks which are present in the company processes, installations and management systems. Lindhout and Gulijk (2011) noticed that the challenge of "unknown risk" is often treated along the line of "fully unknown, hence we cannot act on it". Chemical companies in nearly all cases appear to be dealing with "partly unknown risk", leaving the know part unattended.

Widely spread is *poor learning from accidents* (Lindhout et al., 2019; Lindhout and Gulijk, 2011), leading to underrepresentation of known accident scenario's which have happened in accidents in the past in situations similar to those in the company concerned.

Accidents are traditionally allocated to technical causes, for example leakage due to corrosion. The importance of non-technical causation in scenarios is being *underestimated*, for instance due to language issues which can cause misunderstandings (Lindhout and Gulijk, 2011) or due to unsafe risk taking behaviour (Flin et al., 2000). A scenario is not always originating from a single point failure. It is not uncommon for companies to be only looking at *single failures only* rather than also at multiple factor causation and *systemic risk* (Edwards et al., 2012). This leads to formulating risks rather generally, thus hiding 'the devil in the details'. Finally, scenarios may simply be *overlooked* and escape attention during the often comprehensive analyses companies undertake to build their *risk inventory*.

Secondly, there is the kind of risk that is conceivable but at the same time considered to be extremely *unlikely*. Therefore any effort to reduce such risk is deemed as a waste of time and money. Hence, experts might acknowledge such a scenario but do nothing about it except for accepting it as *residual risk* for economic reasons (Ale and Mertens, 2012).

Thirdly, some risks are not fully understood. Not all about a danger might be known. The associated risks remain *unidentified* for a part or perhaps even in its entirety, no matter how hard the company safety experts try. There can be *unknown risk* (Lindhout and Reniers, 2017A), of which one can either be aware, hence it should be named

'known-unknown' risk, or unaware, hence to be called 'unknown-unknown' risk (Petersen et al., 2013) (See also Fig. 1). Although essential for dealing with the latter mysterious and sinister 'unk-unk' problems - because *unknown* does not necessarily mean *not foreseeable* - such a distinction is rarely made (Ramasesh and Browning, 2014).

Arguably the *fourth* pitfall is the claim that some risks are *normal* (Perrow, 1984, 2011bib_Perrow_1984bib_Perrow_2011) or *not foreseeable* (Galen and Bellamy, 2015), e.g. due to the sheer number of possibly harmful combinations of conditions or events, and the *interdependency* or interaction (Ale et al., 2014) between the many elements in the complex systems of chemical process plants. Funtowicz and Ravetz (1990), Paté-Cornell (1996) and Petersen et al. (2013) mention several kinds of *uncertainties* leading to imprecise-, unreliable-, statistically varying- and even unknown elements in company assessments of foreseeable risks. This suggests that foreseeable risks might have a not foreseeable part associated with them.

The *fifth* pitfall is *entropic risk* (Mol, 2003) and the *dynamic aspects of risks*; instead of snapshots of which risk assessment approaches are focused upon today. Movies of risk (levels) should be made by using dynamic risk assessment techniques and approaches since situations and circumstances change all the time, hence also their associated risks.

Obviously any unknown risk, as a result from either of these pitfalls, is probably at the same time an unmitigated danger, or, from current safety management systems point of view, an uncontrolled risk. Such a risk jeopardises effective major accident prevention by the safety engineer and threatens worker safety, it puts the environment in harms way and endangers company continuity.

1.2. This study deals with the question

What can the safety engineer in the chemical industry do about unknown risks?

2. Method

Exploring 'unknown risks' poses a challenge to traditional methods for systematic literature review. A *body of knowledge* with harmonized and settled terminology does not exist here (Ören, 2005).

Therefore the authors did not aim for a systematic review but chose instead to explore literature as available via Research Gate, Academia and Google Scholar with associated proprietary databases.

We applied the scoping review technique (Smith et al., 2015) and used a screening process (Byrne et al., 2016; Byrne, 2016) with search terms and in/exclusion criteria. To this end several consecutive searches were done, using progressively refined and combined (sub-)sets of search terms, derived from the introduction- and problem definition sections.

Since the research question concerns the present day discourse, the search time period was set to 2010–2020. Due to their particular relevance, a few sources published before the year 2010 were admitted.

The initial search terms were: "*Chemical industry, safety risk assessment, major accidents, risk inventory, unidentified scenario, paradigm*". From the initial search result, sorted on relevance, the first 200 sources were screened to find relevant sources and new search terms. Then, successive searches with different combinations of the terms "*dropping accident rate, learning from accidents, worst case, systemic risk, residual risk, unlikely risk, uncertain risk, unknown risk, not foreseeable risk, interdependent risks, entropic risk, dynamic risk, emerging technology risk, unknown risk*" were used to further refine the search.

Finally, further sources were identified via reference listings of sources as encountered.

The quality of the sources admitted is safeguarded by selection of primary and secondary scientific sources (Cronin et al., 2008) as an inclusion criterion. By exception, because of their relevance, also a few tertiary sources (Wessels, 1997) were admitted. The authors analyse current thinking about safety by asking questions about paradigms being

		Knowledge	
		Known	Unknown
Awareness	Known	Take measures KK	Do academic and industrial research on the risk KU
	Unknown	Constant attention, Follow up Do safety studies (e.g. Hazop) UK	Sense of vulnerability Creativity, Be pro-active on: "what else?" UU

Fig. 1. Knowledge, Awareness and what to do about accident scenarios (after Gowland, 2011).

debated, problem solutions being proposed, how to proceed and in which direction to move.

Then, looking for a way forward, and inspired by Peirce (1867), Le Coze (2013), Gowland (2011), Hansen (2018) and Lindhout (2019A), the authors propose a philosophy based map of reality. To this end they construct an *existence field* in the major accident prevention world. Unknown, hence uncontrolled risks can be depicted as phenomena in this field, depending on their position or movement along an *unknown-ness scale*. The field and scale are combined into a tool to select a suitable action approach for each (partly) unknown risk.

An example taken from an inventory of 'known-unknown' risks as derived from lived experiences in the chemical industry by Lindhout (2019A) and several general examples are assessed with this scale.

Finally, the discussion section sketches a way forward towards more complete risk assessments.

3. Results

Several successive questions guided the authors during this study. The path they followed is described in this section as a narrative account of the exploratory process the authors went through. Many questions were found rather than answers.

3.1. How to handle unknown risks?

An Accident is basically a sequence of events leading to the release of energy or toxicity in an unwanted and uncontrolled way. Such a sequence is usually referred to as a scenario. In a complex high-risk chemical process plant, many accident scenarios are possible.

The EPSC (European Process Safety Centre) places such a scenario in a matrix of awareness versus knowledge, each being either known or unknown (Fig. 1). In the resulting square the unknown may be at the awareness side, then requiring constant attention, keeping a sense of vulnerability and conducting safety studies. It may also be at the knowledge side, then requiring academic and industrial research. When both sides of a scenario are unknown, everything is needed, together with creativity and a pro-active approaches around the question "what else?" (Gowland, 2011). Clearly the position chosen by the EPSC is not a vote for merely accepting "unknown risk" as a fact of life, neither is it a vote for regarding it as a phenomenon which safety management will not be able to do anything about.

3.2. What about the paradigm debate?

So, how to go about this? Here, unsettling debates between paradigms are overwhelming the safety engineer with many questions about how to deal with (partly) unknown risks:

- Is what *safety management* currently does about safety in High-Risk Organisations still effective, sensible and logical (Le Coze, 2013; Hopkins, 2014; Kampen et al., 2018)?
- Should we run process plants as if they were *nuclear submarines* (Bierly and Spender, 1995)?
- Would *safety clutter* be the first problem to solve (Rae et al., 2018)?
- Is *safety culture* as a concept ("the way we do things around here") really clear, well understood, effective and useable in practice for everyone involved (Hopkins, 2018; Vierendeels et al., 2018)?
- Are companies considering safety as a priority or as a *value* (Rat-ilainen et al., 2018)?
- Can safety management keep up with the pace of *emerging technologies* including all of its new risks (Kingston-Howlett et al., 2016; Pillay, 2015; Leveson, 2004)?
- Is the ongoing multiple phenomena degradation of process installations sufficiently well understood to be able to both increase production volumes and keep it safe while moving *beyond the original process plant design life time* (Selnes and Ersdal, 2011)?
- Might safety managers for some reason *ignore* any risks (Gjerdrum and Peter, 2011)?
- What risk is still *hidden, unforeseeable or unknown* with the current knowledge, methods and systems at the disposal of safety management (Lindhout and Reniers, 2017A)?
- Are risks *dynamic* rather than static and might they be *continuously changing* (Mol, 2003)?
- Is there enough and adequate collaboration and transparency, so that practitioners learn from each others *near misses* and incidents (Gnoni and Lettera, 2012)?
- Is there *adequate inspection* and are company safety management systems being improved adequately based on lessons learnt from accidents (Accou and Reniers, 2019)?

3.3. Which problem solutions are proposed ?

Many solutions are being proposed, resulting in as many questions:

- Is our *mental model* requiring a turn towards 'total respect' (Blokland and Reniers, 2017)?
- Is it all merely a matter of *perception* (Slovic and Weber, 2002)?
- Should regulator inspectors be less soft and cooperative and exert more pressure, choosing the *hard line* instead (Kelman and Hong, 2016)?
- Or do we most of all need to *improve* on what we are doing in terms of gathering evidence (Sun, 2012)?
- Or might it be the *anticipatory thinking* (Klein et al., 2007) we need to embrace?

- Is it possible to avoid problems by more emphasis on safety during the *design* phase (Husin et al., 2017)?
- Could process installations be made completely *inherently safe* (Ahmad et al., 2017; Nemet et al., 2018)?
- Or can we just cover any uncontrolled risk with *resilience engineering* (Hollnagel et al., 2011; Haavik et al., 2016; Sujun, 2018; Hopkins, 2014; Pillay 2017; Wiig and Fahlbruch, 2018; Leveson, 2004)?
- Can we mathematically predict the effects of uncertainties via *evidential or credal network analyses* (Misuri et al., 2018)?
- Are risk assessments getting better with ‘*Safety-II*’ in mind and looking for what goes well (Hollnagel, 2014; Sujun et al., 2017)?
- Would it be possible to *rule out human error* in situations requiring fast and smart response to unforeseen danger (Bellamy, 2018)?
- Can we still rely on *safety culture* to further reduce accident rates (Groeneweg et al., 2010; Guldenmund, 2018; Vierendeels et al., 2018).
- Could safety culture be enhanced by *nudges* to induce safer behaviour on voluntary- and even involuntary basis (Lindhout and Reniers, 2017B; Sunstein et al., 2017)?
- Will industry be prepared to embark on integrated design-based safety and security, using a *collaborative approach between competitors* and deploy *cluster teams* (Reniers and Amyotte, 2012; Reniers and Khakzad, 2017)?
- Should we use more *artificial intelligence and sensor technology* aimed at monitoring process safety with a *big-data* ‘nervous system’ which continuously generates real-time scenario safety state warnings in chemical plants (Uraikul et al., 2007). In other words: why don’t we detect increased risk before any containment is lost (Leveson and Stephanopoulos, 2014)?
- Indeed, could the *proactive instant measuring of (un)safety conditions* (Blokland and Reniers, 2019) become the next new paradigm in succession of safety culture?
- So, is it simply a matter of ‘*safety-intelligence*’, providing a constant stream of information about error producing conditions to educate the top executive level (Kirwan, 2008)?
- Or is meticulously following the ISO-31000 risk management standard, prescribing the *identification of all risks*, really the best we can do about the new challenges chemical industry has created since the 1960-ties (Lalonde and Boiral, 2012; Pillay, 2018)?
- Looking at the many alternative safety management system designs (Li and Guldenmund, 2018), could the currently prescribed *seven elements* architecture in the Seveso III Directive hold back company risk mitigation performance?
- What about the relation between *safety and security* (Reniers and Khakzad, 2017; Casson Moreno et al., 2018)?
- Must we keep hunting for *black swans* (Taleb, 2007; Murphy and Conner, 2012; Ale et al., 2020)?
- Is it all about the *art of using the right risk assessment tools* and even modifying them for specific situations like interacting risks (Lyon and Popov, 2016; Dallat et al., 2017)?
- Or are we to embrace *mindfulness* and seek *new thinking* and an *integrated perspective* on risk (Aven and Krohn, 2014)?
- Could *human intuition*, expressed via fuzzy bow-tie models (Zarei et al., 2019), improve risk assessments?
- Would it be enough to work with the *4 assurances* that all technology used is state of the art, management is committed to safety, improvement is continuous and personnel is highly competent (Danner and Schulman, 2018)?
- Apparently the introduction of *12 life saving rules* significantly helps to reduce incidents, so why not taking these up in all Safety Management Systems (Groeneweg and Dijk, 2011)?
- Could an entropic risk model (Mol, 2003), based on dynamic risk assessments and continuous risk monitoring, using *big-data* and new communication technology, help to deal with varying risks?
- Would the systematic multi-paradigm approach via the *Cynefin model* (Blokland and Reniers, 2013, p106; Snowden, 1999; Kurtz and

Snowden, 2003) always converge situations with disorder and chaos towards controlled risk?

3.4. How to proceed?

It would seem none of these proposed ways to proceed will cover the entire problem behind the scenario gap by themselves. Reniers and Khakzad (2017) indicate though that their new *multi-paradigm approach* they call “CHESS”, could lead to major improvements through a combination of several of the above mentioned strategies. However, it is unlikely to be successful in the short term. After a considerable while, practice will reveal whether their combined use has an improvement – i. e. reduction – effect on unsafety or accident rates. Moreover, this should preferably have an impact on safety, besides on unsafety.

Also merely *extrapolating the past* and using an *evidence-only approach* (Pawson et al., 2011) seems not enough to foresee what’s next. For instance, there is doubt whether we can learn enough from accidents and near misses even if we capture all there is to learn from them (Lindhout and Gulijk, 2011; Leveson, 2004). This doubt comes from the notion that we still rely on fixed accident causality recording methods while the pace, in which new technology, insights and methods emerge, indicates that we are entering a *fourth industrial revolution* (Schwab, 2015).

This gives rise to even more questions:

- Should we -first of all-reconsider the way the regulator operates as it is *creating its own disasters* (Black, 2014)?
- Is it sensible to let risks be managed by those that take them for their own economic benefit, and then rely on eight key principles to *solve government risk policy problems* (Aven and Renn, 2018)?
- As we travel with a lack of knowledge in our dangerous, strange, new, complex, interconnected and changing world, are we to revert back to fearing the unknown, just like ancient explorers saying to one another: ‘*here be Dragons*’ (Elahi, 2011)?
- Or do we need to pull ourselves together and move beyond the simple two dimensional *dread versus familiarity factor space*, towards a values based, inclusive, social and psychological model of risk perception (Taylor-Gooby and Zinn, 2006)?
- Is it even feasible to cover all risks in the economy driven *hyperbolic risk space* we seem to live in (Mendel et al., 2015; Reniers and Van Erp, 2016)?
- Assuming we could ever be ready and there is a future moment we will think we have done all the work, could we know whether our search for dangers is actually *complete* (Cantrell and Clemens, 2009)?
- Looking at the permanent influx of new risks a. o. Due to dynamic and *entropic properties of risk* (Mol, 2003), could we indeed ever be ready?
- Would there be, however hard we try to get there, an ‘*unknowable*’ realm we can never get to (Pawson et al., 2011)?
- Could incorporation of epistemology and philosophy come to our rescue (Le Coze, 2013)?

3.5. What is on the horizon?

The rather bizarre consequence of the current probabilistic thinking is that such a thing as a major accident scenario, with its many predicted casualties and major economical damage, could not only exist but also be regarded as broadly acceptable to society, since its risks are properly controlled (HSE, 2001, p43). Such a scenario could still lead to a major accident however, since there often is a *residual risk* to consider and accept. Residual risk frustrates the safety managers’ effort, invested in prevention activities. The safety engineer might wonder whether residual risk is an adversary too strong to fight against. Part of this adversary might be the *cognitive bias* included in the new but trusted big-data safety monitoring systems (Burggraaf et al., 2019). Are safety engineers getting lost in a safety desert, not knowing in which direction

to move (Lindhout, 2019B)? This leads to more questions yet again.

- If all risks are managed to residual risk level, does this thinking imply a *threshold accident rate level* we would never drop below (Mol, 2003)? Would these be the 'normal accidents' (Perrow, 1984) of the future?
- And is that threshold level then collectively creating a *hard core* of many knowingly and consciously taken risks, yet each individually extremely improbable major accidents? Or is the residue a left-over set of minor accidents no longer holding major accident risk content? Would *unknown risk* really be "the safety engineers' best and final offer" (Lindhout, 2019A)?
- While entering a 'new adaptive age of safety', would there still be more to learn from accidents via *organisational learning* (Gillman and Pillay, 2018)?
- Could *total safety management* (Goetsch, 1998; Kontogiannis et al., 2017), *systems theory* (Leveson, 2004; Chi and Han, 2013) or *game theory* (Song et al., 2020; Reniers et al., 2009) lead to a much needed break through in our approach of making a risk inventory?
- Is probabilistic thinking holding the safety managers' endeavour back and is - by default - the *deterministic* approach the only escape here, or might *fuzzy Bayesian networks* (Zarei et al., 2019) and alike, e.g. *Petri-nets* (Zhou and Reniers, 2018; Yazdi and Darvishmotevali, 2019), help us to clear our view on hazards?
- Or would *risk-homeostasis* (Delatour et al., 2014; Rasmussen, 1997) make any further effort by safety science pointless anyway?

3.6. Dead in the water ?

When it comes to perception of major accident risks, society uncomplainingly accepts much greater every day risks, certainly when comparing to their overall yearly consequences found in accident statistics on damage and casualties (RIVM, 2003). Society tends to forget rare incidents and is suddenly awakening each time one happens. The bright flashing effect of a single major incident outshines the glow of many smaller incidents. Society appears to react much stronger to the rare flashes than to the always present glow. The authors contend that society has not yet reached equilibrium between economy and safety, and at the same time wonder whether this conundrum might be solvable after all (Reniers and Van Erp, 2016)? The way forward is unclear anyhow.

It comes as no surprise that Taylor-Gooby and Zinn (2006) conclude that risk research suffers from a wide range of perspectives. It would seem that the drops in industrial accident rates since the nineteen fifties, following the successive introductions of safety technology, safety management and safety culture, have arrived at a plateau (Hudson, 2007; Swuste and Reniers, 2017; Reniers and Khakzad, 2017; Le Coze, 2013). Without an effective theoretical framework about (normal) accidents and high reliability organisations (HRO) (Hopkins, 2014), with stagnating accident rates, many new thinking directions in all sorts of directions and probabilistic methods making rare accidents a legitimate phenomenon, the safety engineer appears to be standing clueless at crossroads.

So, are safety specialists at their whit's end here? Would this be the end of safety science as we know it? Are they at the limits of what is humanly possible in terms of risk control in the chemical industry? Is it getting impossible to reconcile the differences between scientific-, social-, ethical-, economical- and technical insights when it comes to a complete and properly controlled risk inventory? Are they facing an impenetrable territory of ignorance? Confronted with all these thinking directions, safety science seems to be stuck in a *liminal space* (Lapadat, 2017), remaining indecisive, not knowing what direction to go, floating 'dead in the water'. Safety science seems in desperate need of a new paradigm at the brink of the *third safety revolution* (Reniers and Khakzad, 2017). Can safety engineers perform a "Von Munchhausen act" (Raspe, 1785) and pull themselves out of this existential swamp?

On the contrary - in the authors view - many possibilities still exist to achieve improvement through all of the above, but this requires inquisitiveness and a generally applicable method allowing the safety engineer to systematically work on hitherto deemed 'unknown' - and left alone - risks.

4. Analysis

4.1. Phenomena and existence field

Wondering where to go next, the authors contend that it would seem practical to proceed with the hitherto barely touched unknown risk part in the scenario gap problem. It is the realm where ideas about future developments and new risks, like the ones originating from emerging- and ageing technology, come together. It was Le Coze (2013) calling upon epistemology and philosophy to come to our rescue here.

Still 'dead in the water', the *unknown* could become the safety engineers' new horizon...

Philosophy may offer a proverbial 'tow-boat' here. Already the earliest scientific thinking about the world, as we experience it around us, included a notion that *there is more* than we are aware of. Something that the Greek philosophers would consider as a known part of physical reality, appearing from direct observation via the senses, was labelled a 'phenomenon'. Any remaining, assumed to be existing but as yet undiscovered part of reality was called 'noumenon' (Kant, 1781; Warburton, 2011). Science in general and phenomenology in particular, are geared to discover and understand phenomena coming from this mysterious realm (Merleau-Ponty, 1945). Although some phenomena may not immediately appear (Heidegger, 1927), and much of the phenomenologists' effort is focused on investigating subjective lived experience in people's lives, rather than facts in the physical world, the basic question in phenomenology: "*How does the world appear to human consciousness?*" (Husserl, 1969) might be helpful to explore undiscovered things in safety science. This differs from the stance taken by the scientists in physics, when they empirically explore '*the real world*' beyond what is currently detectable with human senses and their extensions in the form of technical equipment (Humphreys, 2004). But how to reach for the unknown of which we are ignorant?

In line with current mainstream philosophical thinking, reality can be mapped with any sure known 'phenomenon' in the centre, transitionally less known concentric domains around it, and a completely unknown, 'noumenon' domain at its outskirts (Hansen, 2018), as shown in Fig. 2. A complete '*saturated*' phenomenon (Marion, 2002) can consist of parts scattered over the different domains in this existence field. Some part of a phenomenon is known, some of it is not fully known, some of it is not known though knowable, some of it is not known at all.

In each of these domains a different strategy is required to move knowledge about what is going on there in the direction from the unknown outer rim towards the known area in the centre (1). The centre represents the every day world where cognition and practice rule, where empirical science can build evidence. The first domain around the centre is an area dominated by ontology (2), where we need suspiciousness, wondering, learning, debating, and finding new words to describe things not seen before. The next domain, another step further from the centre, is the realm of intuition (3), coincidental discovery and changing our values and views on the world. Even further 'out there', is the unknown domain (4) where mystery and wonder rule (Hansen, 2018). Here passive listening is needed, receiving apophatic experiences and events where a phenomenon might show itself. Wondering and looking at the world like a child without prior knowledge. This dark and mysterious realm requires apophatic thinking and keeping an open mind, looking for what is not said and what is hidden in between the lines (Arendt, 1978). Postulating an even more distant domain (5) in order to make the distinction between *knowable* and *unknowable* has little practical meaning since the latter - if existing at all - can neither be known nor dealt with (Ramasesh and Browning, 2014). In Fig. 2 this distinction is

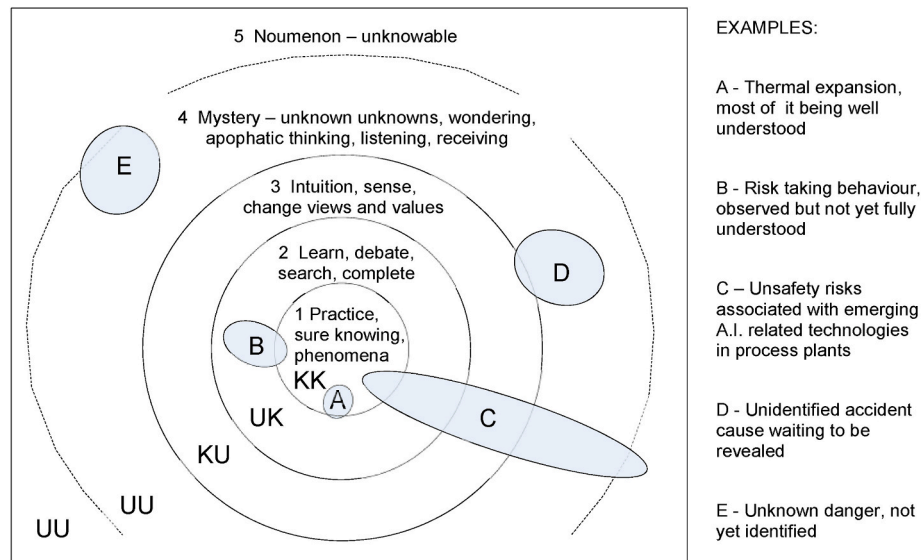


Fig. 2. Reality: a map of the world around us in five domains with example phenomena (Derived from: Hansen, 2018). UU, KU, UK and KK refer to Fig. 1 quadrants.

indicated with a dashed outer perimeter.

Everyday life examples of safety related phenomena and potential phenomena A to E, scattered over the concentric reality map domains (1) to (5), are shown in Fig. 2. An example of a danger exclusively residing in domain (5) cannot be given.

Example A is a phenomenon not immediately visible to the naked eye but discovered a long time ago: *thermal expansion of materials*. This physical effect was e.g. used to shrink wrought iron threads on wooden spoke wheels. Very little remains unknown about this and as a phenomenon it resides in domain (1) touching at the border of domain (2) since each new material needs investigation.

Example B is a partly known and partly to be further investigated phenomenon: *risk taking behaviour*. It varies with many personal, cultural and other aspects (Ji et al., 2018). It sits for a small part in domain (1) but mainly in domain (2) as there is much left to be better understood (Flin et al., 2000).

Example C, the *safety hazards associated with Artificial Intelligence (A.I.), robotics and the internet of things*, are only partly known and under control. These emerging technologies also invade industry, including chemical plants, and bring as yet unknown dangers along with them. They are subject of many studies (Burggräf et al., 2018) to learn more about them since part of its hazards are currently not known. And there is more. The fear that A.I. could get a mind of its own and act on that, that A.I. might fall into the hands of the wrong people, or economically disrupt society, is no longer mere science fiction. Several years ago scientists started to realise there are potential risks A.I. holds which are not understood or known. Steven Hawking (2014; 2017; 2018) identified these as a matter of serious concern. As A.I. is expected to supersede human intelligence one day, machines might disclose parts of reality that remain unknowable to mankind. This leads to A.I. depicted as a partly understood and partly potential *saturated* phenomenon residing in domains (1), (2), (3), (4) and (5).

Example D, an *accident cause not yet revealed*, is unknown except for its suspected existence, and resides in domains (3) and (4). In Arizona, a self-driving vehicle killed a pedestrian in March 2018 but it took until May 2018 for the mysterious cause – a software glitch – to become clear (Efrati, 2018).

Example E is a *danger, currently not known to man*, that could either be discovered or not. It waits in domain (4) and may have a part in (5). Radiation sickness was an example of such unknown danger in the years before 1900, when ionising radiation was only just discovered. It was Marie Curie warning for its health effects after she had damaged her

fingertips, and had contracted leukaemia. She died of radiation sickness in 1934 (Goldsmith, 2004).

4.2. Risk unknown-ness scale

As (Kloman 1992, p300) already wrote in the early nineties: “... Perhaps the real objective of risk management is to reduce fear of the unknown and the unexpected, and to create confidence in the future”. Reniers and Khakzad (2017), when facing the many unanswered questions about how to break free of the ‘plateau’ and start to improve safety again, conclude that “... In order to truly advance safety a paradigm shift is needed”.

Preparing for the unexpected requires things like attention for *weak signals* (Delatour et al., 2013), *embracing failure* in its full depth and detail and – preferably – having hands-on knowledge of the plant to really understand what is going on (Weick and Sutcliffe, 2007). Like accidents, also risks can be classified by type. Terms such as *major accidents* (Veld, 2015), *black swans* (Taleb, 2007) and *normal accidents* (Perrow, 1984) are often used. Important lessons are being learned via this thinking.

A safety engineer would handle *uncertainties* in knowledge and data as an attribute of a known phenomenon or risk. Such uncertainty would e.g. refer to variation of a quantifiable parameter or a not precisely determined probability of an event (Paté-Cornell, 1994, 1996bib_Paté_Cornell_1994bib_Paté_Cornell_1996).

For this study though, in our endeavour to support the safety engineer while exploring the unknown domains of process plants reality, a generally applicable scale indicating ‘unknown-ness’ is needed. In order to look at movement in the continuous knowledge flow associated with increasing awareness, and with moving from unknown (noumenon) towards the known (phenomenon), at least some stepping stones between the two extremes, as already acknowledged by the Greek philosophers, would come in handy. Peirce (1867), the founder of “pragmatism”, used a simple three stages approach for this and coined them *Firstness*, *Secondness* and *Thirdness*. Firstness is about a condition, existence, possibility, not yet thought about, understood or described. Secondness is about emerging relations between facts and observable things, exposing differences, objects and interactions. Thirdness is about recognizing patterns, allowing naming, connecting, grouping, classification, arranging, explaining, predicting and anticipating. In other words: something is almost.

Getting known to the extent needed to identify it as a phenomenon.

Peirce (1867) three stages between phenomenon and noumenon compare rather well to the four domains in the reality field map, reflecting current mainstream philosophical thinking (Hansen, 2018), as is shown in Table 1. The unknown-ness scale is designed to structure a description of the current company situation of - as yet not fully known and not properly mitigated - risk at a particular moment. In this study we use the domains 1 to 5 and a merged description of ways to gather knowledge in each of the domains.

4.3. Uncontrolled risks inventory

Lindhout and Reniers (2017A) present an inventory of unmitigated hazards as derived from regulator experience in the Dutch chemical industry. Out of the 44 unknown risks they present, one is ‘unknown-unknown’ and one is a hypothetical, well known and controlled generic risk that qualifies as a phenomenon. They mark respectively the upper (domain 5) and lower (domain 1) extremes of the unknown-ness scale. The other 42 risks are in between and belong in the transitional domains (2), (3) and (4) since they have some sort of awareness, a named condition or a consciously made choice, associated with them.

Lindhout and Reniers (2017A) analyse these 42 risks (See Table 2) and show that some of them are more known than unknown, and therefore already qualify as a ‘phenomenon’. Hence, some 9 of these 42 risks are not only suitable for direct investigation but also for taking action.

Out of the remaining risks, some 18 can be allocated to domain (2) on the scale since they have a mix of known properties and identified attributes on the one hand and a lack of knowledge on the other for specific and identified aspects.

A further 9 risks can be allocated to Domain (3) on the scale because, apart from conditions and possibilities in which these hazards might come to expression, little more is known about them.

This leaves some 7 risks in domain (4) with only awareness of their existence as a basis.

In Table 2 this set of uncontrolled risks found in the Dutch chemical industry is grouped (but not prioritized) according to the unknown-ness scale in Table 1 in the domains (1) up to (5).

This set of uncontrolled risks compiled from experience can be used by the safety engineer as a starting point. The inventory list can be extended with company specific issues as necessary. Actions can be allocated and progress can be monitored. This opens up the possibility for the safety engineer to also work with (partly) unknown danger in a structured way using a risk inventory and action list (RIAL).

Table 1
Proposed unknown-ness scale compared to three existing scales.

Domain Origin	1	2	3	4	5
Reality in Greek philosophy	Phenomenon Known reality	Noumenon Unknown			
Reality Stages Peirce (1867)	Phenomenon Known reality	Thirdness Recognizing patterns, allowing naming, connecting, grouping, classification, arranging, explaining, predicting and anticipating	Secondness Relations between facts and observable things, exposing differences, objects and interactions	Firstness Condition, existence, possibility, not yet thought about, understood or described	Noumenon Unknown
EPSC awareness versus knowledge matrix (Gowland, 2011)	KK Known knowns	UK Unknown knowns	KU Known unknowns	UU Unknown unknowns	
Reality mapping Hansen (2018)	Ontic Cognitive, every day, facts, empirical evidence, sure known	Ontology Learning, debating, new terms, new things	Intuition coincidental finds, changing values and views, passive listening,	Mystery Apophatic thinking, open mind, wonder	
Proposed Unknown-ness Scale (this study)	Practice Ontic Cognitive, every day, facts, empirical evidence, sure known.	Learn Ontology, Thirdness, debating, new terms, new things, Unknown knowns.	Intuition Secondness, sense, coincidental finds, changing values and views, Known unknowns.	Mystery Firstness, Passive listening, apophatic thinking, open mind, wonder, Unknown unknowns.	Noumenon Open mind, wonder, Mystery. Unknown unknowns, Unknowable

4.4. Proposed action approach

The proposed way to go about using Table 2 based action approach is detailed in sections 5.4 and an example is included in section 5.5.

For each of the domains on the scale the most important action needed to achieve reduction of an unknown, uncontrolled risk is to find out more about it and move it along the “unknown-ness” scale – and towards the top of Table 2 – in the direction of a well understood phenomenon, at domain (1)/Practice. There, among known phenomena, an identified danger can be taken up as an action by safety management so the previously uncontrolled risk can be brought under control. This can be done with conventional methods for identification of risks and definition of appropriate measures (ISO, 2009; EC, 2012).

In practice this is not immediately possible for all uncontrolled risks in domain (2), (3) and (4). The further up the scale, the more difficult it will be to move them towards domain (1). For hazards in domain (2)/Learn, measures can often not yet be taken since there is insufficient knowledge available to define them. The most important action to be taken here is investigating the hazard in order to gain understanding and bring them to domain (1). Then design and implementation of measures becomes possible.

Hazards in domain (3)/Intuition, can not be directly investigated and brought to domain (1). The domain (3) hazards require both attention and time. In terms of action, the safety engineer can take such hazards up in a structure to gather information, make records of observations, and be on the look-out for situations where they could emerge. A new way of thinking might be needed to enable understanding and gain insight (Hansen, 2018). The objective here would be to bring a domain (3) hazard towards domain (2) in due course.

Hazards in domain (4)/Mystery, are foggy and fuzzy and they require curiosity and creativity to somehow get a grip on them. This is where a *what-if session*, *creativity* or *serendipity* while talking about something could make all the difference. An open mind is needed since information about hazards can suddenly appear at unexpected times and places (Csikszentmihalyi, 1996; Hansen, 2018). These bits and pieces may indicate what to look for though. The objective here is to move domain (4) hazards in the direction of domain (3) so they can become subject of information gathering.

Finally, hazards in domain (5)/Noumenon, may suddenly be revealed by a coincidence, or by simply looking at the right place on the right time. Then something noticed can be recognized as belonging to a hazard. This requires an alert and receptive safety engineer. Domain (5) hazards may also remain hidden in the mysterious outskirts of reality

Table 2

Risk inventory and action list (RIAL) showing unmitigated hazards identified in the chemical industry (after Lindhout and Reniers, 2017A), their domain allocation on the unknown-ness scale and a proposed action approach.

Risk Inventory and Action List (RIAL)		
Unknown-ness SCALE	Unmitigated hazards inventory	Proposed action approach
Domain 1 Practice, Phenomenon, Ontic, Known's, KK	<p>[Known and correctly controlled generic risk]</p> <p>Remaining risks of known and probabilistic controlled danger</p> <p>New compulsory safety measures not yet taken by companies</p> <p>Known danger currently excluded by the regulator</p> <p>Known danger being ignored as a risk</p> <p>Known danger previously excluded by the regulator but currently included</p> <p>Non-compliant measures allowed and not noticed by the regulator</p> <p>Risk improperly controlled and in excess of acceptance level</p> <p>Known danger as yet unmitigated waiting on the action list</p>	<p>Take action to reduce and/or control these risks.</p> <p>Apply: Excellent risk management (Blokland and Reniers, 2013)</p>
Domain 2 Learn, Thirdness, Ontology, Unknown Knowns, UK	<p>Measures announced but not yet prescribed by legislation or standards</p> <p>Danger too unlikely to occur to be under risk-control</p> <p>Danger not considered because of economic or strategic reasons</p> <p>Measures not taken for well-known frequently occurring accident types</p> <p>Danger due to improper use of additional risk calculation factors</p> <p>Danger due to cost cutting on safety critical items</p> <p>Danger due to outdated classification in accident investigation</p> <p>Known danger remaining unmitigated due to failing countermeasures</p> <p>Known risk improperly controlled due to wrong chance or effect data</p> <p>Measures not up to the state of the art</p> <p>Measures no longer state of the art but still allowed by outdated permits</p> <p>Danger due to standard-rather than specific hazard inventory</p> <p>Danger due to improperly conducted safety studies</p> <p>Risks exceeding acceptance level due to uncertainties in the assessment</p> <p>Known danger not fully neutralized the deterministic way</p> <p>Danger caused by unsafe behaviour</p> <p>Danger due to overestimated barrier performance</p> <p>Rare but occurred scenario</p>	<p>Investigate these risks, plan for bringing them under control and bring them to phenomenon domain (1).</p> <p>Apply: Just Culture (Dekker, 2012)</p>

Table 2 (continued)

Risk Inventory and Action List (RIAL)		
	not identified in company risk inventory	
Domain 3 Intuition, Secondness, Known Unknown's, KU	<p>Unknown danger due to loss of expertise with change of personnel</p> <p>Unknown danger due to staff unfamiliar with intricacies of old/new plant</p> <p>Unknown danger due to interface problems during building the plant</p> <p>Unknown danger due to exceeding the design lifetime of a plant</p> <p>Unknown danger due to lost overview of risk inventory by subcontracting</p> <p>Unknown danger due to underreporting of danger</p> <p>Unknown danger due to poor registration of incidents</p> <p>Unknown danger caused by new technology</p> <p>Unknown danger due to wrong assumptions for scale-up</p>	<p>Study these risks by observing & recording finds, change thinking on views and values, gathering information to bring them to Thirdness domain (2.)</p> <p>Apply: Questioning attitudes (Bierly and Spender, 1995)</p>
Domain 4 Mystery, Firstness, Unknown's, UU	<p>Danger we are not aware of but could be if we thought about it</p> <p>Ignorance at both company and regulator sides</p> <p>Danger remaining undiscovered due to low regulator priority</p> <p>Unknown design flaws</p> <p>Underestimated risk</p> <p>Danger obscured by information overload</p> <p>All other possible things that could go wrong but were not identified</p>	<p>Use intuition, be curious, creative and suspicious. Attempt to bring your notions to Secondness domain (3).</p> <p>Apply: HRO approach (Weick et al., 2008; Turner and Pidgeon, 1997)</p>
Domain 5 Noumenon, UU, Unknowable	Unknown danger nobody could possibly know about	<p>Keeping an open mind at all times, wonder about the mystery (Hansen, 2018).</p> <p>If one appears place it in Firstness domain (4).</p>

where nobody happens to be looking in the rare case a hidden danger shows. In domain (5) meaningful planned action is not possible except keeping an open mind to remain able to notice any mystery revealing part of itself.

4.5. Example

As an example to illustrate how the inventory in Table 2 can be interpreted, extended and used in practice, the “*Danger we are not aware of but could be if we thought about it*” mentioned in the first inventory line of domain (4) is used here. The proposed action for domain (4) risks is: “Use intuition, be curious, creative and suspicious. Attempt to bring your notions to Secondness/domain (3) “. This would lead to the following course of action:

The safety engineer, aiming at the new and unknown safety horizon, could gather a few critical and knowledgeable people and walk around the plant together. This curious and creative team can ask each other questions about anything they see underway that might have a bearing on safety. This *safety walk* (Kletz, 2001) is a routine in many companies. Generated notes, questions and remarks should not be restrained, excluded or criticized however. Afterwards, the safety engineer gathers the subjects addressed by the participants and checks if these are already mentioned in the existing inventory list of ‘unknown’ risks (see initial

list example in Table 2). New subjects are added to the bottom of the list in domain (4). Subjects that were raised earlier are placed higher on the inventory list, thus getting more priority. Any such prioritized subject requires a short discussion in a regular safety management meeting to agree on how to further investigate this signalled issue and its potential risk. This brings the issue from domain (4) on the inventory list to domain (3) where -over time-more information is gathered about it. Next follows a traditional research effort in domain (2) and finally, risk management will start once the danger is brought to domain (1). These steps constitute the steps of a systematic process which is gradually bringing unknown, hence uncontrolled, risks towards the centre domain (1) where they can be turned into actions by the company safety management system.

5. Discussion

Having the uncontrolled risk types identified, listed and prioritized, how can safety managers move forward? The proposed action approach brings existing but hitherto unknown risks out in the open.

Hence, *first* of all it is advisable to synchronize watches with company management. Suddenly looking beyond the existing company safety horizon might open a Pandora's Box of safety issues. Normally in a company, facing fierce competition, any surprise that could cost money is most unwelcome. The evidence of a positive relation between safety excellence and economic return needs pointing out (Fernández-Muñiz et al., 2009).

The *second* thing would be to adapt both the company management view and perspective towards non-acceptability of unknown risks, directly followed by changing their view on the world of major hazards. Any company management could be inspired by Hansen (2018) and simply not stop wondering about the dark and gloomy mystery staring them in the face every day.

And then, *thirdly*, there is important work to do: actively and systematically looking for new horizons and new scenario's. For the safety engineers it is all about getting to the full depth of their individual passion for safety (King and Artym, 2003): respecting the environment and protecting and saving peoples' lives, preferably the ethical way. In Table 2, the right hand column action approach can be used as a tool to systematically work on reduction of the unknown-ness in the uncontrolled risk inventory, adding measures as necessary. This tool allows continuously and systematically improving safety, as opposed to coming to a halt by settling for the existence of 'unknown risk' and accepting it as 'fate' or 'a fact of life'. In other words: increasing the risk appetite (Gjerdrum and Peter, 2011), as in industry, a lack of "risk appetite" leaves risks unmitigated and this practical and systematic approach is expected to help the safety engineer to work on this more effectively.

The ongoing multidirectional scientific research for better risk control paradigms, concepts and methods does not interfere with this practice oriented approach. On the contrary, the authors contend that the method proposed here does not exclude any of them. The risk inventory and action list, as presented in Table 2, although not yet complete for a specific company, does offer a beginning. The safety engineer needs to be inquisitive, always on the lookout for new subjects on the horizon to investigate and add them to this inventory. Big-data and new smart technology might be used to assist this work (Figueres-Esteban et al., 2018; El Rashidy et al., 2017).

Participatory action research (PAR) may be a possible tool to evaluate pilot studies in industry with the proposed action approach based on Table 2 (Borda, 2006; Kemmis et al., 2014; Reza, 2007).

As industry keeps developing new ways to handle hazardous substances, new hazards, new insights, and new known-as well as known-unknown risks emerge all the time. Risk entropy and dynamism necessitate abandonment of the static one-off risk assessment. In this way any risk can be included in the proposed risk inventory and action list (RIAL). Hence, over time, also the hitherto deemed unknown safety risks can be systematically brought under control.

6. Conclusion

The immediacy of the stagnating long term downward major accident rate trend, as observed in the Netherlands and Belgium, underlines the need to address the uncontrolled risks caused by various safety management pitfalls as mentioned in this study. Current safety practice is apparently not effective enough to leave the current plateau in the long term incident rate trend. Both companies and regulators not only need to do better in their current ways, but, moreover, need to be more eager in systematic reduction of currently unidentified and unknown risks, in order to accomplish further dropping of the major accident rate. Although no final closure can be reached here, the main conclusion for now is that both the safety engineer and safety management can never be ready with hazard identification and risk assessment. Finding a sound, safe and systematic way forward may require the combined strength of 'old school' *philosophical inquisitiveness* and new '*multi-paradigm*' systems thinking. Finally, the fundamental question remains whether any risk assessment will ever be complete.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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