The Need to Establish Consistent International Safety Investigation Guidelines for the Chemical Industries

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1. Introduction

Traditionally in the chemical industry, safety engineering has been based on the fact that risks can be predicted in most production processes. But this becomes increasingly difficult when systems become more complex in a dynamic network. In most cases complexity is increased because chemical plants form part of open socio-environmental-technical systems and because toxic products may cause harm for humans and the environment. In these circumstances, accidents can be caused by new, unforeseen mechanisms. At the same time, the global reach of complex supply chains creates new interdependencies between manufacturing units. The safety of chemical processes should be supported by the harmonization of incident and accident investigation across national borders. If accident investigation practices are better aligned the knowledge related to rare, unanticipated interactions could be shared and possible prevention measures created. The concepts, models and methods that are in use across the chemical industry are very different from those within the aviation industries. However, the chemical industry is in a strong position to learn from the practices already available in other industries, in particular in civil aviation and nuclear power generation. Although these practices can't be accepted without modifications they are applicable in developing safety investigation processes and practices.

2. Accident Investigation Practices in Aviation Industry

The early origin of the international aircraft safety investigation process can be traced back more than 70 years (Johnson and Holloway, 2007, Stoop and Kahan, 2005). In 1944 the International Civil Aviation Organisation (ICAO) approved Annex 13 of the Chicago convention. This established the basis for international co-operation in safety investigation in major accidents. Since then this Annex has been updated several times (ICAO, 2010). The most important principle is to prevent similar types of accidents from occurring again. As a result of investigation, there are always some safety recommendations for the local company or national authorities or occasionally for the international airline industry or international aviation authorities. These safety recommendations may go beyond current regulations and legislation. Usually the recommendations will be given within 12 months after the accident, but if needed it is possible to give urgent recommendations even when the safety investigation process is still going on. If criminal investigation proves necessary, it is carried out separately in most countries. Such separation is mandatory by ICAO Annex 13 regulations so that all parties in an accident are encouraged to contribute in identifying safety recommendations.

2.1 The state level of investigation

ICAO Annex 13 defines the stakeholders who can take part in the safety investigation process. In summary, the country in which an accident occurs will usually assume responsibility for coordinating an investigation. Annex 13 also provides for the participation of representatives/investigators from the country in which an aircraft or its major components were manufactured. Additional representation is provided for the country in which the aircraft was registered as well as from those countries, which represent the nationality of deceased passengers. This increases the number of participating countries, the number of investigators and may also complicate the investigation process. The extensive participation of different stakeholders serves the objective outcome of the accident report and assists in implementing the final safety recommendations; it reduces the likelihood of subsequent disagreement. The first objective is to achieve consensus on the description of the course of the event and to better understand the failure mechanisms that caused the event, building on available evidence. The second objective is to share information and to achieve recommendations that can be of value for the aviation community by supporting common learning processes. It increases confidence in an investigation by increasing the transparency of investigatory processes. During the early stages of an investigation the aim is to collect as much relevant evidence as possible. It is important to avoid hindsight bias and to look beyond the sharp-end; beyond individual actions to consider the systemic aspects of an accident. Hindsight bias uses evidence that was not available at the time of an accident to make unwarranted judgements about the behaviour of individuals and groups involved in an accident. It is often coupled with a 'perfective bias' where the focus is on blaming the operators and engineers directly involved in the final events before an accident. In major aviation accident investigations, the classic 'pilot error' has been balanced with an increasing focus on the organisational factors that create the context in which an error is more likely to occur. The 'sharp end level' is more common in occupational accident investigations (Vuorio et al, 2014) and arguably also in the offshore and process industries. 'Blame free', or more correctly 'proportionate blame', investigations have achieved recognition in aviation and are formally arranged in Annex 13.

The investigation must consider a range of human factors including the clinical (both physical, medical and mental) and forensic concerns addressed in the ICAO Civil Aviation Medicine protocol (ICAO, 2012), The fundamental purpose for medical investigation is to “determine the facts, conditions and circumstances pertaining survivability or non-survivability”. The prime objective for human factors investigation is to “obtain evidence through an examination flight crew, cabin crew and passengers”. In aircraft safety investigation, autopsies and toxicological analysis are routine stages in the forensic investigation. This data provides valuable knowledge of the survivability aspects in the accident. In addition to investigations into the causes of an accident, a separate investigation into the performance of rescue and emergency services is often conducted by safety agencies. As examples can be named Turkish Airlines flight 1951 at Schiphol (Dutch Safety Board, 2009) and Asiana Airlines flight 214 at San Francisco (National Transportation Safety Board, 2014).

Most countries, which have adopted the ICAO annex, have established permanent organisations to investigate aircraft accidents. This may be an independent aviation accident investigation branch or part of a multimodal accident investigation authority, for instance also covering road, rail, maritime industries. Usually these organisations only have a small permanent staff of investigators – responsible for management and control over the investigation process. They are also allocated a very limited budget that is increased whenever a major investigation has to be conducted. These agencies hire specialists for issues of long term concern and experts in specific domains, when needed for particular accidents. Investigators In Charge, as defined by ICAO Annex 13, are trained in advance for their tasks and are capable of leading a ‘go-team’ during the on-site phase of an investigation. The use of this ‘go team’ approach reduces costs of permanent in-house specific experts and increases the flexibility to mobilize on a ‘on demand basis’ additional range of technical expertise that can be called upon by permanent investigators.

ICAO Annex 13 and the associated techniques do not resolve all of the practical problems that complicate accident investigation, especially for smaller states. Given a very low probability of a major accident each year, it can be hard to justify the funding required to train and maintain the expertise of highly skilled permanent investigators (Johnson et al., 2014). Some countries have share training costs with neighbouring states and specializing in specific domains such as the analysis of digital flight or rail recorders, photogrammetry or human factor analysis. This has led to the development of multi-modal investigation agencies where permanent staff is expected to lead investigations into incident and accidents across the rail, aviation and maritime industries. On the other hand, past experiences have demonstrated the threat of losing proficiency and domain specific expertise through ad-hoc investigation committees and parliamentary inquiries. In general, independent investigation agencies not only focus on major accidents; they also address trends, patterns, safety concerns and specific categories of accidents with a safety learning potential. Cross modal investigation capabilities focus not on *what* to investigate, but *how* to investigate. We argue that such problems can only be avoided by cross-modal investigations that share a sound methodological basis and common competence across investigators. In addition, due to the wide variety in legal and social contexts, investigation agencies must adapt to very different local operating environments. Some agencies have remained single mode (BEA, AAIB, ASC), become multimodal (NTSB, TSB of Canada, ATSB and JTSB) and even multi-sectoral (Sweden, Finland, the Netherlands). Boards have an integrated organisation (DTSB, NTSB), a federal organisation (UK), interstate cooperation (Russia) and even continental (Australia).

2.2 The European level

The European Union (EU) has adopted the ICAO framework as a part of European Parliament Regulation (European Union, 2010). As a consequence of the European Union framework for air safety investigations and the subsequent Directives, a European Network of Civil Aviation Safety Investigation Authorities (ENCASIA) was established. The Network constitutes an independent grouping of the air safety investigation authorities of the EU Member States. Its establishment is envisaged by the recently adopted Regulation (EU) 996/2010 on the investigation and prevention of accidents and incidents in civil aviation.

2.3 The international level

Beyond the level of national investigation agencies, the aviation industry is characterized by a series of unique international institutional arrangements. At the international level, safety in aviation is organised at the institutional level. As already stated, the most prominent organisation is the UN organisation ICAO; the International Civil Aviation Organisation. In addition to its Annex 13 investigation procedures, ICAO has an Accident Investigation and Prevention Division, which organizes regular Accident Investigation Group Divisional Meetings for state representatives and Panels on topical issues, such as flight data recorders. Under the auspices of ICAO the Division disseminates standards and recommended practices. AIG meetings are also attended by International Observer Organizations, such as ISASI, the International Society of Air Safety Investigators as the organisation of professional qualified air safety investigators. ISASI is organized along lines of world regional chapters and organises annual international seminars. It provides mutual assistance and information sharing of investigation findings and safety research. ISASI organizes Reach out Workshops for states to support less qualified and experienced investigative professionals in their conduct of investigations. Investigating incidents may serve as a trigger for change, sharing knowledge on specific phenomena that are accessible through accident and incident data repositories of organisations that operate on a sectorial level such as the Flight Safety Foundation FSF. Such patterns of safety concerns are also disseminated by professional organisations of investigators, such as the ISASI.

2.4 Leading transport safety investigation agencies

As a spinoff of two international congresses on the safety of transportation, an international cooperation between leading transport safety investigation agencies has been established (SoT, 1992, SoT, 1998). On October 22nd 1993, the independent investigation boards of the United States, Canada, Sweden and the Netherlands met and agreed to form the International Transportation Safety Association (ITSA). ITSA was founded on the notion that independent non-judicial investigations of transportation accidents contribute significantly to the safety of the traveling public, and that an international organization, which brings together the accident investigation agencies from many nations, would be mutually beneficial forum to share safety information. Today, ITSA is composed of the independent investigation boards from 15 countries (ITSA, 2012).

Over the past 20 years, the member agencies have seen four consecutive phases:

- Establishing independence from state interference and developing a multimodal focus. This phase lead to the recognition of a need to develop –mostly in-house- a dedicated investigation method and specific training of investigators.
- Expanding the scope of the investigation towards new actors and aspects. Victim support and family assistance have led to the recognition that independent and qualified safety investigations are a Citizen’s Right and Society’s Duty (Van Vollenhoven, 2002)
- In order to deal with growth in all transport modes, high level policy making in the EU, ICAO and IMO acknowledged the value of independent investigation agencies. This acknowledgement is reflected in various EU Directives, ICAO and IMO resolutions. Several serious events outside the transport modes expanded the scope to the public domain, creating institutional safety arrangements at a national level
- A need to cooperate and coordinate during international investigations, disclosed a need to create knowledge and expert networks on an institutional basis. Regional cooperation, linking investigations to specific research networks became crucial. Cases such as MH370 indicate unprecedented challenges with respect to big data mining efforts, satellite reconnaissance and ICT applications in tracking and tracing.
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2.5 Adaptation to new challenges

A new phase has been considered; to provide a repository of past performance for shared learning. Cases such as China Airlines flight 611 and Malaysian Airlines MH17 indicate the need to achieve consensus on the course of an event, based on agreed findings and evidence. During this incremental adaptation to changes in the operating environment of safety investigation practices, four different roles can be distinguished, each contributing to a specific purpose of sense making and meaning (Dekker, 2014.1, 2014.2):

- Epistemological: providing knowledge about the event under scrutiny
- Preventive: safety enhancement and avoidance of undesirable consequences
- Moral: transgression of moral and ethical boundaries
- Existential: explanatory relief of suffering of victims and relatives.

Dekker distinguishes two different explanations for the fact that different epistemological narratives of the same event may exist in parallel. Political sense making may explain how established interests in an investigation can be shielded by divergent interpretations and conclusions. Political sense making may also explain how competent investigators and investigation authorities may come to different conclusions and recommendations. In overcoming such differences, the plea for independent investigation agencies has seen a long tradition (Van Vollenhoven, 2006). A second epistemological explanation refers to the various purposes of an investigation in constructing an explanatory description of the event. In addition to the accuracy of such a description, the plausibility, credibility and verifiable completeness of the available knowledge must guarantee the trust of every party involved in the event. Achieving consensus on the course of the occurrence by providing descriptive and explanatory variables creates a basis for further analysis, adaptation and identification of change variables in coping with systemic and knowledge deficiencies (Stoop, 2015).

3. State of the art in the chemical industry

The following sections build on our analysis of existing practice across global aviation to consider the contrasts with investigations in the global chemical industries.

3.1 Lessons from Bhopal catastrophe

Thirty-one years after the Bhopal catastrophe, we can identify important lessons into the problems created from a lack of planned or coordinated accident investigation practises. In contrast to the apparent strengths in aviation investigations, when a toxic cloud of methyl isocyanate (MIC) accidentally escaped from the Bhopal pesticide plant on 3rd December 1984 it led to what were arguably ad hoc investigations by the companies involved and by the Indian government (Abraham, 1988; Bisarya and Puri, 2005). The non-governmental Centre for Science and Environment (CSE) was one of the first organizations to publish a descriptive report of what happened at Bhopal (CSE, 1984). While this report provides a valuable description of the catastrophe events and consequences, it lacks the detailed causal analysis and generic recommendations that would be expected in many more formal accident reports. Such investigations often restrict themselves to the fact-finding phase in collecting evidence. These initial reports are very valuable in achieving consensus on the overall course of an accident and, thereby, provide foundations for identifying potential causes. The manager, who was responsible for the health and safety in Union Carbide Corporation, published another report in 1993 (Browning, 1993). As might be expected, this provided a particular perspective on the accident that has not been shared in subsequent investigations.

At Bhopal, it is noteworthy that very few autopsies were carried out for the deceased. Some years after the accident, research was initiated to discover the toxicological effects of MIC (Bucher, 1987). In 1984, MIC was not on the list of U.S Environmental Protection Agency (EPA) (Willey, 2014). Currently there is evidence that monitoring of those Bhopal casualties who survived should continue for the next 50 years (Sharma, 2002). This lack of monitoring arguably demonstrates deficiencies in exposure research for toxic substances, especially focused on threshold limits in short term exposure to high concentrations versus long-term exposure to low concentrations.

Despite the lack of a coordinated, independent safety investigation into the causes of the Bhopal accident, the incident did trigger a number of immediate responses. The first US Congressional hearing on the Bhopal catastrophe was held on the12th December 1984. This led to the Superfund Amendments and Reauthorization Act (SARA) (United States Environmental Protection Agency, 2011) and Emergency Planning and Community Right-To-Know Act (EPCRA) (United States Environmental Protection Agency, 2014). EPCRA was created to help communities plan for emergencies involving hazardous substances.

This initiative to support communities in-distress bears resemblance with initiatives in the USA to support air crash victims and their relatives. The Aviation Disaster Family Assistance Act of 1996 and the Foreign Air Carrier Family Support Act of 1997 created a victim support and family assistance organization to facilitate these groups at risk in coming to terms with their suffering. This initiative has been followed in almost every country where air crashes have occurred, in theory placing the air carrier, as well as other support organizations, in a collaborative relationship with families.

3.2 Moral dimension

Many previous studies, for instance by Reason (2009), Rasmussen (1997) and Leveson (2011), have focused on the technical and organizational factors surrounding incident and accident investigations from a managerial perspective. Safety is a corporate responsibility that refers to management responsibilities, primarily defined as a ‘control’ issue with an inherent utility, based on rational decision making principles and inherent normative notions. In contrast, we would also focus on the ‘moral and existential dimension’ for independent safety investigations. Accident investigations are not only technical procedures but they also form an important part in the grieving process for individuals and social groups. In every investigation that focuses on learning independence is the most important priority (Roed-Larsen and Stoop, 2012). If a transparent safety investigation is lacking, the learning process can be ineffective and ultimately this process of grieving may be sacrificed in favor of a continued ‘search for justice’ in the aftermath of incidents and accidents. The judicial process has an important role in determining compensation through the application of Tort and this can indirectly lead to improvement in safety (Hutter and Lloyd-Bostock, 1990) by focusing on ‘sharp-end’ events; seeking to allocate liability and accountability, subsequent blaming individual operators and managers. However, the organizational shortcomings are often neglected or inaccessible for investigations due to the burden of proof that is required to involve higher corporate or governmental levels in the sequence of events.

3.3 US Chemical Safety Board

As mentioned previously, the US Chemical Safety Board (US CSB) provides a template for the development of an independent agency investigating chemical accidents (U.S. Chemical Safety and Hazard Investigation Board, 2014). The unique decision that congress directed that the CSB's investigative function will be completely independent can be seen following the earlier successful model of the National Transportation Safety Board and the Department of Transportation. The aim of this organisation is to carry out safety investigations and to identify recommendations that will improve safety. More specifically, the office will investigate conditions and circumstances, which led up to adverse events and near miss incidents. The law, that no other agency may direct the activities given to the Board also protects investigations. The database of US CSB accident reports, which has already accumulated, contains utmost valuable information and these reports can be used to further improve safety of chemical industry (Fyffe et al., 2016). The way to adopt worldwide US CSB scenario of operation is to establish international agreement with the help of international organisation like it was done with the help of ICAO in aviation industry. This agreement could establish common ground for those safety investigations following major accidents.

The US CSB works closely with both the Environmental Protection Agency (EPA) and the Occupational Health and Safety Administration (OSHA). Importantly, the Board is authorised to carry out investigations of chemical hazards even if an accident has not yet occurred. Such an approach of establishing safety studies for investigation purposes is not uncommon in transport safety investigations. Frequent incidents also are under scrutiny if they represent a safety threat of a more generic and frequent nature, such as Signals Passed At Danger (SPAD's) in railways or Runway Incursions in aviation. Safety recommendations are presented to government agencies, companies, trade associations, labour unions and other stakeholders. As an example, a recent US CSB report focussed on "Metal Dust Explosion and Fire"; the recommendations identified a lack of safety regulations intended to mitigate potential dust incidents (U.S. Chemical Safety and Hazard Investigation Board, 2011). The conclusions were based on a pattern of similar accidents identified across the USA. A number of recent studies have identified similar patterns of safety concerns across the chemical industries (Khan and Abbasi, 1999; Okoh and Haugen, 2013); including studies of incidents across years since Bhopal (Gupta, 1990).

3.4 European Safety, Reliability and Data Association

National agencies, such as the US CSB, are not the only mechanism to improve investigatory practices across the chemical industries. Non-profit organisations can play an important role in developing safety-culture across national borders. The European Safety, Reliability and Data Association (ESReDA) has published their "Guidelines for Safety Investigations of Accidents" (European Safety, Reliability and Data Association, 2009). These guidelines have been created in co-operation with safety experts, safety research institutes and the Joint Research Centre of the EU, representing knowledge domains and industrial sectors across different European member states. As with the ICAO guidance, ESReDA focuses on finding out why the accident happened and not on blame or liability. However, the greatest limitation regarding the ESReDA guidance is the lack of government recognition; the guidance has not yet been incorporated into national or European legislation. The ESReDA guidance also attempts to harmonize the methods used in accident investigation by a bottom-up approach of comparing and combining expertise and experiences.

3.5 The distinct approaches across the "generations" of safety investigations

Recent studies have contrasted three widely used methods in accident investigation. The findings showed that the chosen methodology can have an important impact, for example in sustaining a more systemic view of the causes (Underwood and Waterson, 2014). Greater harmonisation in investigatory methods around the globe would help support the combined analysis of many different accidents and possibly derive new insights for preventive measures. This approach has partly been sketched in recent studies within the chemical process industries (Cowlagu and Saleh, 2015). In general, three distinct approaches can be identified across the 'generations' of safety investigations from an occupational perspective:

1. Metaphors such as the Domino theory, Heinrich's pyramid, the Swiss Cheese model or Risk Homeostasis. Such metaphors serve the goal of communication tools, but hardly have a scientific basis and are by definition, beyond verification, falsification and validation.
2. Single, static, linear models and methods. A vast array of such models and methods exist. They are frequently developed as dedicated tools for specific applications, but lack a wider applicability due to their dedication, linearity or static nature. Earlier work of Benner, Sklet and others indicate their limitations due to absence of a systemic perspective; by focusing on the operational level and applicability by lay people.
3. Complex and dynamic models/methods such as FRAM, STAMP and Accimap have a scientific origin, coping with complexity and dynamics of socio-technical systems. They are relative rudimentary with respect to the state-space dynamic systemic behaviour due to absence of a temporal dimension. A recent study has argued that STAMP does not meet some of the usability requirements of practitioners (Salmon et al. 2012, Underwood et al., 2016). Only very few methods have been developed by investigators themselves, such as the STEP approach of Benner or ISIM from the TSB of Canada (Stoop, 2015). While scientists tend to focus on modelling systems and processing preselected generic data, investigators emphasize the investigation process and methods focusing on forensic

principles and evidence and case based approaches. There is a tendency to expand the scope of modelling into large data systems, applying sophisticated mathematical processing by Bayesian Belief Networks and quantum data processing techniques, while on the other hand socio-organisational modelling takes place in adaptive networks and hierarchical control configurations.

4. Barriers for dissemination aviation experiences and approaches.

During the conduct of an investigation, assumptions, simplifications, inadequacies of underlying accident models and mutual dependencies of investigation methods and accident models may considerably flaw the quality of the investigation results (Benner, 2013, Stoop and Benner, 2015). Consequently, such restrictions should carefully be taken into account examining their results, while a combination of models and methods could provide a more reliable platform for accident analysis (Katsakiori, Sakellaropoulos and Manatakis 2008, Stoop & Dekker, 2010). Assessing the dominant models of Reason's Swiss Cheese and Rasmussen's Systems Hierarchy, Stoop and Dekker discuss implicit methodological assumptions that limit their practical applications as safety analytic tools (Stoop and Dekker, 2010).

- There are underlying barriers that are well known in the –among others- aviation investigators community, but hardly if ever discussed in scientific literature. We have not come across such papers yet. There is a gap between the notions of investigations and research, in particular with respect to the logic of abduction and investigation methodology

- In the literature -in particular in social sciences-, a popular but unsubstantiated prejudice is developing to an assumed obsolescence of accident investigations, to be replaced by managerial notions on resilience. Some even have questioned the existence of safety science as a science. In our paper, we provide arguments that a combined strategy and adaptation of the perspective and notions to new needs and circumstances is more preferable than a battle between disciplines or domains. We first have to clarify underlying mechanisms before we can build a new generic applicable notion and subsequent toolkit.

4.1 Modelling issues

It is widely assumed that it is possible to transfer the concept of independent investigation from aviation to other domains. This assumption is primitive because it does not take into account the specifics and history of the notion of investigations as developed in the various domains. In particular, the assumptions in the notions of Reason and Rasmussen are biased towards management and control.

4.1.1 The Reason metaphor

Stoop and Dekker share the concerns of Reason and Wreathall -the creators of the Swiss Cheese metaphor- about the use of the metaphor as an investigator's model and analytic tool (Stoop and Dekker 2010):

- Remote factors have little causal specificity, are mostly intractable and have no predictive potential. They shift error up the ladder and do not discriminate between normal and deviant system states and do not take into account inherent system dynamics.
- There are no stop rules in expanding the scope. The more exhaustive the investigation, the more remote factors are likely to be discovered.
- The metaphor assumes a linear agent-host-environment relationship, based on an epidemiological, medical concept.
- Technology is assumed a constant, applying a barrier concept for mitigating exposure and consequences, rather than focusing on hazards, inherent properties, adaptation and system architecture.
- It does not deal with uncertainty and knowledge deficiencies, variety in operating performance, various system states or operating envelopes, all of which are crucial in designing and operating complex systems.
- Finally, the metaphor is normative, dealing with implicit norms and values, compliance with standards and regulations instead of human recovery capabilities and resilience.

Such a modelling and accident representation arguably do not meet the investigators' need to explore, to discover unanticipated and unknown phenomena. The use of generic failure types eventually replicates the expectations of the analysts. A translation of human error modelling into practical investigative tools is still in its early phases of development (Strauch 2015, Dekker, 2006). Analysis focuses on disclosure of orderliness of human performance rather than mental states of operators, raising the fundamental question: why did their performance seem reasonable to the operators at the time of the event (Dekker, 2006).

4.1.2 The Rasmussen model

Rasmussen takes the modelling issue of undesirable events one step further (Rasmussen, 1997). He makes the -so far hardly challenged- assumption that stable conditions of the past versus the present dynamic society are characterized by a fast change of technology, steadily increasing scale of industrial installations, a rapid development of ICT and an aggressive and competitive environment, influencing incentives of decision makers towards short term financial and survival strategies. By giving a synopsis of Rasmussen's model it becomes clear that he states that modelling of accident causation is done by generalizing across systems and their particular hazard sources (Rasmussen 1997):

> Risk management should be modelled by cross- disciplinary research, defined as a control problem and serving to represent the control structure involving all system levels for each hazard category. This requires a functional abstraction rather than structural decomposition. Task analysis focusing on action sequences and deviation from standards in terms of human errors should be *replaced* by modelling behaviour shaping mechanisms in terms of work constraints, boundaries of acceptable performance and subjective criteria guiding change. Systems models should not be build bottom-up from individual disciplines, but created top-down by a systems oriented approach, based on control theory concepts. Modelling task sequences and human error are not considered effective for understanding behaviour. Rather than striving for control of behaviour by fighting deviations, the focus should be on making boundaries explicit and developing skills to cope with boundaries. By stating safety performance objectives, safety becomes just another criterion of multi- criteria decision-making and becomes an integral part of normal operational decision-making. The safety

organisation is merged with the line organisation, losing its independent position during assessment. Such a shift in position requires explicit formulation of value criteria, and communication of such values down through society and organizations. The impact of decisions are to be adequately and formally considered by ‘ethical accountancy’. According to Rasmussen, defences can be based on predictive analysis. Preconditions and assumptions must be stated explicitly in a probabilistic risk assessment. Therefore, it is not necessary to predict performance of operators and management. Data can be collected during operations and used for a ‘life’ risk analysis. Such a predictive analysis should be much simpler than a priory acceptance of the design. Such performance data can be collected through other sources that accident investigation: incident analysis and expert opinion extraction may compensate for the lack of abundant accident data.

Rasmussen states that models required to plan effective risk management, cannot be developed by integrating the results of horizontally oriented research, but should be *replaced* by vertical studies of the control structure for well-bounded categories of hazard sources, characterized by a uniform control strategy (Rasmussen, 1997).

Depending on the nature of the hazard, Rasmussen defines three classes of accidents, based on their frequency and magnitude:

- Occupational safety with frequent but small accidents, empirically controlled from epidemiological studies of past accidents
- Protection against medium-sized infrequent accidents, evolving from design improvements towards analysis of the latest major accident, where control focuses on particular, reasonably well-defined hazard sources and accident processes, representing a taxonomy of accidents
- Protection against very rare and unacceptable accidents, where design cannot be guided by empirical evidence from past accidents due to a very large mean time between such accidents.

Consequently, design and operations must be based on reliable predictive models of accident processes and probability of occurrences. The assumption Rasmussen makes is that the probability of failure will be verified empirically during operations, even if the stochastic coincidence is very low. Monitoring performance of the staff is derived from the system design assumptions, not from empirical evidence of past occurrences. The taxonomy of accidents depends on the nature of the hazard source and the anatomy of accidents. Rasmussen identifies only a limited series of hazards as frequently observed in the process industry: loss of control of large accumulations of energy (explosions), ignition of accumulations of flammable material (fire) and loss of containment of hazardous material (spills). When the anatomy is well bounded by the functional structure of a stable system, the protection against major accidents can be based on termination of the flow of events after release of the hazard. The basis for protection should be on elimination of the causes of release of the hazard. The hazard itself remains unattended or deemed negligible due to its low frequency assessment.

4.2 Risk, a frequentist and subjective notion

A second methodological barrier between aviation and nuclear/chemical industries refers to the perspective that is chosen for integrating the notions of safety and risk. In aviation, safety has been considered a predominant and integral, -horizontal- notion, without discriminating between occupational, technical, product liability and environmental aspects. In the nuclear and chemical industries, safety is a submissive and integrated –vertical- notion, translated into corporate responsibilities with respect to the notion of risk management, balancing safety against other corporate values. Once safety management systems were introduced in airline operations, safety was transformed from a strategic value to an operational performance indicator.

4.2.1 Risk as a notion

In a historical review on the development and trends in the risk concept, Aven (2012) notices that there is no agreed definition of the concept of risk. Over the last 15-20 years, there has been a shift from rather narrow perspectives based on probabilities to ways of thinking which highlights events, consequences and uncertainties. Although they are still strongly represented, there are arguments against their use. Aven distinguishes between the definition of risk per se and how it is measured. The discussion on broadening the risk concept has been fuelled by publications of leading socio-psychological and economical scientists such as Slovic, Kahneman and Taleb. In the risk domain, various definitions exist in parallel, dealing with probabilities and expected values which can be interpreted in different ways. Basically, two fundamental interpretations discriminate a frequentist –parameter and metrics based-probability versus subjective –knowledge based, judgemental probability. According to Aven, risks based on probability models are to be rejected since such models make only sense in cases of repeatability because such models cannot justify unique events. Aven advocates pluriformity in the scientific risk debate regarding both qualitative and quantitative methods, because a varying degree of uncertainty calls for different methods. With respect to the consequence dimension of risk, the subjective assessment is related to human values and norms, distinguishing between positive as well as negative consequences for different populations and stakeholders. In balancing risk components, a balancing takes place between both concerns in determining what is acceptable and desirable or not and for whom? Therefore, according to Aven, it is not so relevant to classify the outcomes in a right category, it is the activity as such that counts.

4.2.2 Risk modelling

In modelling risk, Robinson notices a difference between military and business oriented modelling of discrete events for simulation purposes (Robison, 2008.1, Robinson 2008.2). Military modelling tends to involve large models with a long life time, developed by teams of clients, modellers and domain experts. Business modelling tends to be an activity of lone modellers, acting simultaneously as domain expert and consultants, aiming at a relatively small scale with a project life cycle of normally less than six months. Since every model is a representation of reality, the modeller is faced with decisions what to include or exclude, balancing complexity versus simplicity and adherence to the context. The quest is for better models, not for the best or most complex model. Modellers have to decide on a satisfactory level of accuracy, data availability, necessary knowledge of the real system for interpretation of the simulation results and efficiency in terms of available versus necessary data, developing time and running costs. The modeller should be aware of his own beliefs, assumptions and simplifications he incorporates in the modelling process. Robinson identifies a need for *conceptual* modelling, differentiating between artefacts of identifying the problem domain versus the model domain. Such a conceptual model is separated from the computer model which is software specific and contains specific computer codes. A conceptual model bridges the gap between the real world and its representation by the model. Unfortunately, in the simulation literature, the process of designing models on a conceptual level is more an art than a science and -but despite that- can be submitted to understanding and training. Since such understanding and training however hardly exists, an explicit transparency and understanding of the scope, validity, assumptions and simplifications of present categories of models is limited (Robinson 2008.1, Robinson 2008.2). Zimmerman et.al. have noticed that practitioners do not have a strong allegiance or adherence to specific models or methods. When the validity of models is in doubt, assumptions are ambiguous and unconvincing or presented out of context, they are not loyal to such a single perspective (Zimmerman, 2011). Stoop and Benner advocate cooperation between developers of new scientific concepts and models and their prospect users population in practice (Stoop and Benner, 2015). Guzetti points out that challenges of new approaches such as data mining and big data processing, recognizing the benefits obtained, should be balanced with realistic expectations (Guzetti, 2014). Therefore, it is crucial for researchers to create tools and methods which are clear enough for users to recall and apply in their daily work (Zimmerman et.al., 2011).

4.2.3 Safety as a science

Simultaneously, in a Special Issue of Safety Science of October 2014, a debate is stimulated on the question whether safety science is a science or not (Hollnagel, 2014). This existential debate raises questions on the fundamentals of safety as a science, deliberating the role and impact of social sciences, risk analysis and organisational concepts have had on the development and practical applicability of safety as a scientific notion in the risk debate.

While the implementation of concepts such as safety culture and just culture prove to be problematic from an academic perspective, practical applications have lead not only to significant increases in safety, but also to a bureaucratization of safety (Dekker, 2014). This bureaucratization revolves around hierarchy, specialization, division of labour, formalizing rules and has brought reduction of harm, standardization, transparency and control. It has however, generated secondary effects with respect that run counter to its original goals. This includes marginalisation of safety initiatives and an inability to predict unexpected events, creates structural secrecy and constraints on organisational and individual freedom. An interesting suggestion made by Dekker in restoring deference for technical expertise and tacit knowledge of subject matter experts such as engineers and operators (Dekker, 2014). In remaining sensitive to failure, there is a role for resilience and adaptation, professional expertise, restoring the relations between process safety, system safety and occupational safety, readdressing competence and commitment over compliance. Such developments grew out of a necessity to cope with new challenges, although these concepts are in their early phases of implementation (Hollnagel, Nemeth and Dekker, 2008, Hollnagel, Paries and Wreathall, 2011, Woods, 2016, Esreda, 2015).

Complying with the Reason and Rasmussen assumptions on linear, static and hierarchical representations of accidents by performance modelling and mathematical control algorithms, two major limitations can be identified. First, such a reliance on applying a single strategy in risk assessment, requires failsafe software, high reliable modelling and flawless decision algorithms. This is not yet reality. Second, the assumptions as applied in PRA based risk assessment, run short in such epistemological explanations. They lack two different forms of formal logic in describing and explaining accidental events: abduction and construction.

4.3 Other forms of logic: abduction and construction

A third methodological barrier between aviation and nuclear/chemical industries has its origin in the difference between the scientific understanding of research versus investigation. These two notions refer to the nature of their activity: finding the truth whether or not with a degree of academic uncertainty versus achieving confidence in a plausible and credible explanation of events in order to prevent their recurrence or their unacceptable outcomes. To our knowledge the English language seems to be the only language in which a distinction exists between research and investigation. A lack of such a distinction in other languages may have contributed to concealing methodological differences between the two activities.

In scientific research, two methods of reasoning prevail: deduction and induction. However, there are two more methods; abduction and construction. Abduction is characterized as the logic of discovery, while construction is related to the logic of invention and design (Eekels and Roozenburg, 1991). In 1955 Peirce introduced the logic of abduction (Levin-Rozalis, 2015). Abduction is very powerful and effective in constructing and validating explanations of new findings. Abduction is applied as a tool for evaluating explanations of findings especially in those cases where quantitative, controlled trials based on rigorous universal variables and standards are not possible and generalizations raise serious questions. This is especially true in cases with unfamiliar environments, different cultures or variables that are not clearly defined or do not exist (Levin-Rozalis, 2015). Abduction is ideal for examining hypotheses where the process of discovery is as important as the proof, meeting criteria of logic. In such a process of discovery, new and surprising facts are confronted with the hypothesis, creating an initial explanation that is tested against all observations and facts. In this cyclic process, explanations become broader, more abstract and more general, exploring a wider scope of data and converting explanations into hypotheses. With this logic of abduction, an inseparable link is created between new surprising facts that are observed in a perceived reality and their explanation. Explanations in themselves do not constitute a theory. Examining the hypothesis against the facts and findings of reality against the entire body of observations enables acceptance of the hypothesis as a scientific result. Interpretations of observations are based on *raw data*, collected on-scene providing feedback from reality, not pre-processed into taxonomies or categories of measurable or quantifiable variables. Such observations should be modelled into building blocks of information for further analysis (Benner, 2013).

While deduction and induction aim at finding the truth and certainty of explanations, abduction as the logic of discovery infers to the *best* explanation available. In this process it is necessary to distinguish between the logic of discovery and the logic of proof. Both deduction and induction are unsuited to deal with the process of discovery because they are unable to *explain* discoveries (Levin-Rozales, 2015). Induction deals with phenomena whose range of variance is already known, generalizing from a sample to all phenomena under scrutiny. Induction is applied in a situation where empirical generalization already has taken place. Deduction start within a known theory in order to refute it. The theory dictates the relationships between the concepts and the way in which they vary. Verification of the theory is restricted to known constraints, methods, variables, predefined parameters and metrics. Deduction is an instrument for checking theories, while induction is an instrument for checking probabilities and assessing uncertainties. The logic of discovery is a two stages process: the first stage involves choosing the explanation, the second deals with its examination. In the interpretation and application of the data, clarification is required in order to provide credibility, plausibility and consistency of the explanation that is derived from such data. In a multi-actor and unstructured environment of accident investigation, such data collection inevitably give up a strict control over the data collection process. The conversion of explanations into hypotheses finishes when all available facts and findings are congruent with the explanation. Such an explanation moves away from the immediate facts and findings and becomes more generalized beyond individual cases, revealing patterns, trends and explanatory mechanisms. Deficiencies in knowledge that emerge from such explanations may trigger further scientific research in safety critical topics of a specialized nature. The logic of discovery forces the investigation team to apply forensic principles and scrupulous management of the investigation process. In evaluating the acquired knowledge, such a team should carefully be aware of its own biases, world views, values and norms, avoiding to become judgmental and remain open and receptive to discovering new data as possible. Consequently, safety investigations are never closed: they may be reopened once new data become available.

4.4 Risk acceptance in practice

A fourth methodological barrier between aviation and nuclear/chemical industries may be originating from differences in actor perspectives that exist between aviation and nuclear/chemical industries. In aviation the ultimate responsibility in the safety critical decision making process is allocated to the pilot. To this purpose the notion of Good Airmanship has been developed. In the other industries, the ultimate responsibility for safety and risk is at the corporate level in either a line or staff responsibility. This difference also creates differences in appreciation of the Zero Accident Vision concept.

According to Lannoy (2009), selecting a strategy with its emphasis on the responsibility of management, three scenarios can be foreseen for the future of risk management. First, risk management is a priority when risk are accepted by the public, creating an obligation for industry to optimize safety and performance, balancing safety versus economy and the environment. When in a second scenario safety is not accepted, risk management is reduced to the development of protection and preventive measures and controls. A third scenario emerges when there is no transparency within safety studies, short term discussions are dominant, often not scientific nor clearly elaborated. Such a scenario leads to a ‘soft consensus’ mode without a shared acceptance of the risk. In referring to Beck’s book on ‘Risikogesellschaft’, to avoid the third scenario, Lannoy states that any risk analysis must be systematic, including technical, environmental, regulatory, social, political and ethical aspects. Political and social processes determine the attitude towards risk acceptance, costs, benefits, communications, feelings of inequality of exposure and inevitable residual risks. All these problems are risk management problems at a societal level beyond corporate responsibilities (Lannoy, 2009). In this governmental risk concept, the objective is not zero risk, but reducing the frequency of accidents to as low as reasonable practicable. While appreciating that accidents can happen, contingency plans and adequate responses must be organized to return to normal situations (Ognedal, 2008). The additional challenge is the management of risk associated with operational decisions (Yang & Haugen, 2016). There is often very short time between the implementation and the decision and in most cases industry lacks the practises and capability to analyse the risks in these situations. Moreover it has been recently shown that it is recommended to use actual accident and incident reports compared to expert opinions as the basis of risk analysis to achieve best risk-control and to find out areas that need more research (Mazaheri et al., 2016).

According to Hale, this concept of putting emphasis on risk management could be exemplary for further progress in safety in the transportation industry (Hale, 2009). He points out that despite increased traffic volumes in railways and aviation, both industries have been receptive to the lessons learned in chemical and nuclear industries (Hale 2009). These industries have embraced the notions of an explicit safety management, based on extensive risk analysis and a positive safety culture, *rather than relying largely on the implicit professionalism of their staff*.

All new technology and infrastructure should be subject to a detailed safety case, while safety management should be audited and certified. Such achievements remain major challenges due to privatization and intense competition, retaining safety as a main priority. Since transport is only completely safe when it does not physically move, virtual travel for passengers and goods and enhanced telecommunications will give rise to significant safety improvements (Hale, 2009). Improving comprehensive risk modelling techniques are required to understand better what the most cost-effective ways are of achieving safety objectives, balanced against other costs and benefits from transport, in order not to become too risk averse. He claims that a zero accident philosophy is not realistic; residual risk will always remain. Claiming zero accidents as a goal denies conflicts of balancing aspects of safety against economy and environment. According to Hale, claiming Zero Accident Vision is a hard and shining ideal, subordinating all other goals to their one vision of the right path to salvation or paradise (Hale, 2006).

5. Modelling a generic concept of safety investigations

Most safety investigations in the chemical industry are not primarily based on sophisticated modelling endeavours. Industrial practices provide a reality check for the models and engineering design approaches, often proposed in academia. In aviation, existing investigations tend to be evidence and knowledge driven; using case data and hard-earned domain knowledge to disclose phenomena that have not been recognised before. Such safety investigations represent a specific school of safety thinking by providing a timely transparency in the factual functioning of systems. They rely on the competence of investigators to manage the investigation process and make judgements calls on the quality of the results and progress of the investigation, allocation of resources, applying stop rules, mobilizing specific expertise and support, while communicating with the outside world. How does this work out for initiating a shared concept of accident investigations across industrial sectors and across national borders?

5.1 Towards adaptation of investigation practices

There have been attempts to harmonize practises in specific industry sectors. A relatively recent example is the regulation of the Norwegian petroleum sector (Bye et al., 2015). This has focussed on developing the Health and Safety Environment (HSE) culture to be part of improvement in focus on safety improvements. The HSE culture has become a specific topic or focus for subsequent accident investigations. This has partly helped to understand the complexity of how industry and society interact with each other. In a recent study of 12 industrial accidents or incidents, the authors identified the common need for tools that can be used to diagnose organizational vulnerabilities in socio-technical processes (Taylor et al., 2015). The organizational and cultural precursors could also be important targets in chemical industry accidents. However, the analysis must be done carefully using a suitable technique with a particular focus on the decisions the company has made immediately after the accident (Strauch, 2015).

There are more recent accidents that help to illustrate our concerns. In particular, failures in national regulatory culture and in institutional safety culture have been identified as causes of concern in the Indian nuclear industry from the design of prototype fast breeder reactors (Ramana and Seshadri, 2015). The concerns that arise in extending appropriate safety culture into development practices have also been identified in studies of Taiwanese incidents (Chen et al., 2015). The authors stress the need for new forms of safety training. Only those professionals coming from safety educational programmes were able to increase the value of existed safety programmes.

In addition to common practices in safety investigation; databases are needed to improve learning across national borders and between industry sectors. Such databases may reveal trends, patterns and themes, which are open to further analysis on a case by case basis or at the level of safety studies in specific safety concerns. There have been many advances. The European Union maintains the Major Accident Reporting System (MARS) and in the U.S.A. the respective database is called Risk Management Plan (RMP)-Star (Pitblado, 2011). These reports may be used for safety education (Shallcross, 2013). These ‘lessons learned’ applications have not been widely used in India following the Bhopal accident. This concern is not isolated within emerging economies. The Toulouse explosion in 2001 can illustrate this. The plant was located in the outskirt of the city. It led the French government to completely revise areas of their risk management regulations; in particular focusing on the management of subcontractors (Salvi and Dechy, 2005) and the interference of high-risk industries with land use planning issues and urban development.

Useful lessons have also been learned in offshore planning, where a gradual erosion of prohibitions and regulations may exacerbate the consequences of subsequent accidents (Sarshar et al., 2015). The future challenges include unexpected environmental impacts. An example of good practice in this respect is provided by databases that have been created to analyse and anticipate the damage caused by earthquakes to of pipelines (Lanzano et al., 2015). In the maritime sector environmental and wild life preservation issues have raised great concern due to major events with large crude oil carriers and spills, characterised by the names of the vessels such as the Amoco Cadiz, Exxon Valdez, Sea Empress, Torey Canyon, Erika and many others. The recommendations following these maritime disasters triggered considerable attention at the highest governmental level and institutions such as the International Maritime Organisation (IMO) and the EU, issuing their Resolutions and Directives. The Fukushima disaster triggered interest in the interrelations between natural disasters and collateral technological consequences. These common concerns show the potential for greater integration of the lessons that have been learned on a case by case basis from very different accidents around the globe.

5.2 The rediscovery of accidents: Zero Accident Vision

Others however, advocate a case for research into the zero accident vision. Originating from aerospace technology in the sixties (Stoop, 1990), the Vision Zero concept was introduced in road safety in the nineties of the previous century and has settled as a Safer by Design concept in designing sustainable cities (World Resources Institute, 2015). To enable a better understanding and support of safety strategies, Zwetsloot et al. (2013) advocated the introduction of the concept in companies as the Zero Accident Vision (ZAV). Such a ZAV should reduce hidden costs and low quality and simultaneously promote a zero waste and zero emission strategy and managing the unexpected. A meta-analysis does not give strong support for introducing compulsory Safety Management Systems. Many improvements in safety have been the result of practical applications rather than a result of scientific research. Emerging issues, events and trends have had a big influence on the development of risk management, such as scepticism about effective solutions for the energy challenges (Chernobyl), the introduction of the precautionary principle (for environmental protection under uncertain conditions), the transition to the year 2000 (the millennium bug), raise of terrorism (9/11) life time management of infrastructures (collapse of bridges and buildings) and the financial crisis (inadequate financial risk analyses and management failures) (Lannoy, 2009). Introducing ZAV should support overcoming existing dilemmas and limitations that affect the progress of safety in companies. The concept should facilitate progress beyond linear and rational safety analyses dealing with dynamics and complexity in preventing accidents causing death and permanent injuries. ZAV should provide an additional approach to the High Reliability Organisations and Resilience Engineering concepts in monitoring failure and successes and the necessity to learn from mistakes. ZAV notes existing differences between occupational and process safety approaches and safety cultures, creating unanticipated major accidents such as the Macondo blowout and the BP refinery disasters. A distinction is necessary between various types of events in various contexts, taking into account differences in risk perception across stakeholders. Accidents should be considered rational events that could have been prevented taking into account auditing of the right procedures and regulations and subcultures in organisations of engineers, operators and executives (Zwetsloot et al., 2013). ZAV is based on the belief that as a goal, all accidents are preventable on either the short or long term, mobilizing ethical arguments for the commitment of all actors and integration of their values. ZAV could reinforce existing managerial strategies of innovation, leadership, ethics, commitment, coping with variance, incorporating resilience and advocating research in ZAV notions and concepts. In advocating ZAV however, Zwetsloot et al. do not yet include efforts on improving the diagnostic potential of accident investigations by enhancing safety investigations as a methodology and training of investigators.

5.3 Changes in methodological perspectives on safety investigations

Two major changes can be identified in a transition of focus from a safety research and risk management methodology to safety investigations: application of forensics sciences and an investigative process.

The adherence of forensic principles requires application of forensic sciences. Forensic sciences for safety investigation purposes are defined as (Stoop, 2015):

- Forensic sciences comprise of the science, methodology, professional practices and engineering principles involved in *diagnosing common types of accidents and failures.*
- The determination of the causes of failures require familiarity with a *broad range of disciplines,* and the *ability to pursue several lines of investigation simultaneously.*
- The objective of the investigation *is to render advisory opinions to assist the resolution of disputes* affecting life or property.

Investigative processes can be characterised by three principal phases (Stoop and Benner, 2015):

- An *explanatory description*, based on forensic principles for collecting raw data. Traditionally this is the domain of field investigators in aviation, operational experts and experienced operators, collecting raw data during on scene and post-scene activities
- *Analytic interpretation*, mobilizing (multi-)disciplinary knowledge and sectorial, specific expertise. This phase enables the step from understanding the event into intervention in the system. Traditionally, this is the domain of safety analysts and disciplinary experts, academic researchers and modelling.
- *Adaptive intervention*. This phase is based on both previous phases, applying engineering design principles, problem solving paradigms control strategies and scoping various solution domains for a credible and feasible safety enhancement. Traditionally, this is the domain of engineers, manufacturing and system development.

In aviation, this investigative process has seen a development over the past decades into a sophisticated international network of professional and qualified investigators. This investigative community is unique in the sense that it has demonstrated a high degree of resilience and adaptivity to changing challenges in complex and dynamic operating environments due to a series of institutional arrangements:

- An international repository of experiences and expertise, collected since the inception of aviation itself and preserved in independent organisations and institutions such as the Flight Safety Foundation and national air safety investigation agencies
- Providing a governmental framework at a sectorial level, such as with the mandatory ICAO Annex 13 rules on independent investigations in order to prevent recurrence of similar accidents and incidents
- Skilled investigators, organized internationally through their association ISASI
- Established credible and competent leadership in conducting major events at an international level and at a large scale, requiring multiple resources and competences
- Ability to suppress noise and confusion generated from unstructured interferences from the environment by timely transparency and open communication on accuracy, completeness and plausibility of facts, findings and discussion on feasible and credible recommendations on technical, organisational, cultural or governance issues raised by the investigation.
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6. Applicability of an accident investigations framework for the Chemical Industry

Previous sections have highlighted ICAO Annex 13 and good practices in aircraft accident investigation. However, it is important to stress that we cannot simply extend these provisions directly to the chemical industries. These processes developed gradually over decades and in many countries there is no corresponding level of expertise in investigatory training or practices within the process control domain. It will take time to encourage international co-operation, independence for investigatory organisations, a multidisciplinary perspective chemical accident investigation etc. Although between various chemical industrial plants practices may be more variable than in aviation industry it is likely that common accident investigation protocols could be created also for chemical industry. Maybe it is not so much the protocols but the methodology that counts. Protocols are formal frameworks, while methodologies answer questions on *how* to investigate rather than *what* to investigate. Such harmonisation of investigative protocols depends on the institutional arrangements that can be enforced on an industrial sector by regulation or through voluntary compliance. The benefit of this development includes improved safety by learning from incidents and accidents. No industry can afford to ignore safety concerns given the growing cost of litigation, threats to business continuity, and the moral imperative both to save lives and protect our common environment. Loss of public confidence, allegations of hiding safety-related recommendations, threats to business continuity and the availability of a reference function for settling disagreements are critical in such developments.

7. Requirements for necessary changes in perspectives

The Chemical process industries will meet four major challenges when creating integrated practises for accident investigation. These are 1) how to ensure independence of the investigation process, 2) how to ensure the holistic scope of investigations, 3) how to establish common methodologies for investigations and 4) how to train competent investigators? (Roed-Larsen & Stoop, 2012).

7.1. Independence

Usually independence is based on a legal mandate for an accident investigation organisation, which guarantees its independent position. The National Transportation Safety Board (NTSB) and the US CSB provide blueprints but they are not ideal prototypes for all contexts. However, in the long-term national legislation should guarantee the independent mandate of the organization carrying out an investigation. In addition to legal independence, the national organization needs to have financial freedom. Based on experience in the maritime and aviation sector, it can be argued that independence is best achieved if the national accident investigation organisation is working as a functionally independent organization and not as a part of another governmental organization, especially if that parent body is also responsible for the promotion of an industry (Stoop, 2004). This kind of thinking could be quite challenging currently in some countries but it is the only way to guarantee not only the formal but also the functional independence for investigations. Independence, which is guaranteed in national law, should not lead to over bureaucratization. This can undermine safety initiatives and hamper the flexibility of these organizations. Bureaucratisation will eventually discredit their innovative potential and competiveness (Dekker, 2014). To create and retain independence, competence, credibility and impartiality, the chemical industry should create its own structures to solve these challenges. Structures cannot be directly copied from the aviation industry. They are different socio-technical systems. New structures are needed to face sudden innovative developments, to recover and adapt through incremental changes, coping with their changing structure and culture.

7.2 Holistic scope and methodology of investigations

The practical experience from the Norwegian petroleum industry shows that it is important to create accident investigation methods, which can be used when analysing complex socio-technical systems to address the complex underlying causes of accidents in safety-critical industries (Okstad et al., 2012). This more considered approach relies on 'systems thinking' not only in chemical industry safety investigations but also in general in safety investigations related to industrial accidents (Goh et al., 2014). Complexity is present not only in structures and processes in the chemical industry but the interactions between companies, regulators and their supply chain in dynamic operating environment (Dien et al., 2012) under specific market constraints and business model assumptions. The challenge in systems thinking is to scale up beyond the specifics of a particular event to a wider perspective. This means that the experiences of several scientific disciplines are needed during the course of safety investigation in order to guarantee professional credibility and trust in the validity of recommendations among fellow-experts (Stoop and Roed-Larsen, 2009). Le Coze's analysis of the 2003 accident in a French dynamite factory provides a clear example of organizational investigation demanding the knowledge of several experts (Le Coze, 2010). The need of experts who can be involved in chemical industry safety investigations will be one of the major challenges, especially when trying to analyse complex accidents following natural hazards (Nyman & Johansson, 2015). There is a need to clarify investigation processes and explore inherent assumptions in different methodologies given that different techniques will support different perspectives on the causes and recommendations that may be derived in the aftermath of an accident.

7.3 Creating an international institutional framework

As described, safety investigations in aviation are not conducted in isolation. They take part in a wider institutional framework on an international basis, serving the aviation industry as a whole. They supersede levels of individual organisations, states and stakeholders. In this respect, aviation is organized along lines of international cooperation, not along lines of multinational companies. There is a close cooperation in sharing information and disseminating experience and expertise between all actors and experts in the industry, research institutes and professional and governmental organisations. By doing so, they have relied to a large extent on historical roots in accident investigations based on tacit knowledge, field experience and subject matter expertise. This past performance has brought the industry to a Non-Plus-Ultra-Safe performance level. Within the aviation safety investigation community, challenges are defined to cope with a next generation of aviation technology, business modelling and social innovations. Applying in solitude of existing models and methods such as SMS, PRA and human factors have met their limitations as demonstrated respectively by the investigations into the Macondo well blowout, Fukushima power plant and air crashes dealing with high altitude upset recovery and stall prevention.

7.4 Training competent investigators

A number of different organisations offer training for aviation safety investigators worldwide. There are long-term programs, which provide comprehensive support for investigatory agencies. There are also short-term courses available for industry safety investigators. However, these courses either focus on particular, narrow techniques or a broader superficial perspective. It can be argued that a new generation of investigators is required to cope with the challenges of a rapidly changing operating environment (ISASI, 2014) as well as new areas of safety investigations like safety leadership (Pilbeam et.al.,2016). So far governmental organisations have not been very active in this training field. International harmonization in chemical safety investigations depends on establishing long-term training programs for safety investigators working in this field. There seems to be a dedicated role for sectoral and disciplinary specific education and training to match both requirements from a physical scientific, social dynamical, contextual and investigative nature.

8. Conclusions

We have argued that many countries have learned important lessons for the safety of chemical processes in the years after the Bhopal accident; in particular organisations such as the US CSB illustrate the potential benefits of developing a professional, experienced cadre of safety investigators. However, many countries have still have to learn these lessons – too often reports appear to lack technical competency and the organisational perspective that has informed safety improvements across the aviation and nuclear industries. In addition, there is a need for greater consistency and transparency in the methods used between different countries so that we can have increased confidence in the soundness of recommendations made in the aftermath of chemical accidents and incidents in the transition that is going on from metaphors, via models to methods in safety investigations.

We have argued that ICAO Annex 13, in the context of a wider institutional framework, provides a useful model for the development of common protocols across the world's chemical industries. Despite the fact that total harmonization has not been possible even in aviation industry, the internationally accepted rules how to carry out safety investigations in major accidents have greatly improved overall safety in aviation industry. In systems of chemical industry there exist huge safety risks. If these risks come true international safety investigations will be required. To achieve this target current protocols require transformational rather than incremental adaptations. This has already shown in regarding climate change (Kates et al., 2012). Especially important are those transformational adaptations, which are truly new for the particular industry. Regarding chemical industry, it is very important to harmonize different practices and to secure independent accident investigation in what is a global chemical industry. So far, voluntary initiatives have been taken by experts in academia, research institutes and industry, such as ESReDA by developing guidelines and manuals (ESReDA, 2015). This ESReDA initiative recognizes the need to share a common methodological basis for such guidelines and manuals, legally based on formalized international guidelines, such as the ICAO Annex 13 approach. However, each sector, technology, system and its operational environment poses different requirements and constraints on conducting qualified and independent investigations. A direct 'copy-and-paste' of best practices across sectors does not comply: there is no 'one fits all' approach at the level of investigating sociotechnical systems complexity. In addition to formalized international guidelines there is a great need to educate accident investigators for work within the chemical industries. Existing training programs within the aviation industry can be adapted for this purpose. However, there are important differences – for example in the use of sub-contractors, in the impact of software control and in the technical processes that govern chemical production and distribution. Further work is urgently required to identify competency requirements for the next generation of accident investigators working within these industries. In doing so, the institutional arrangements that dictate the required competences should carefully be taken into account. Despite barriers, of a varying nature, there are opportunities to combine the best of the worlds of aviation, nuclear and chemical industry in order to create redundancy in safety enhancement strategies.

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