Introduction

The Three Mile Island nuclear accident in Pennsylvania, US, in 1979 became a landmark event for risk research. It revealed the limitations of risk analysis and demonstrated that scientific experts and risk managers can seriously misjudge uncertainty in high-risk technologies, misunderstanding and sometimes even having little idea of what goes on behind the scenes. Due to the benefits and critical importance of high-risk technologies such as nuclear energy, civil aviation and chemical industry in modern societies, technological accidents have also contributed to making uncertainty a key issue of our times. Today, uncertainty cannot be overlooked as a key topic associated with the assessment and management of accident risks. In this way, high-risk technologies are an excellent focus for thinking through issues of uncertainty and addressing implications for risk research.

Prior to the Three Mile Island accident, the traditional scientific response related to high-risk technologies seems to have been to look at scientific knowledge as something definitive. Science was to be trusted by society as a guarantee of reliability and safety and served its function best when providing clear and incontestable answers about risk. In this classic worldview on risk research, unknowns are reduced to measurable risk, whilst dissenting interpretations and possibilities of surprise are denied by experts’ scientific methods. However, what happened at Three Mile Island and other disasters opened risk analysis for a wider focus beyond quantitative risk assessment as a scientific mastering of the unpredictable (Short, 1984). Disaster research also became an arena for cross-disciplinary perspectives on uncertainty through themes such as system complexities, sloppy management, cultural secrecy and ignorance (Turner, 1978; Perrow, 1984; Turner and Pidgeon, 1997; Vaughan, 1999). This has influenced and broadened approaches to uncertainty in risk research. In the wider social science literature, uncertainty has also come to figure highly in the sociology of risk. For example, more social uncertainty, amongst other factors related to gender relations, is the basis for the ‘risk society’ (Beck, 1992) and greater individualism (Giddens, 1991).

The emphasis in this chapter will be on the relevance of a broad approach to uncertainty for risk research. The introduction is followed by a section defining uncertainty related to risk. The chapter also includes a framework for distinguishing different types of uncertainty.
This framework relates to different forms of risk assessment and risk management. Following the presentation of the framework, abductive thinking is introduced because it is a fundamental issue that can contribute to the field of risk research by addressing how uncertainty can be maintained and explored. The final part of the chapter provides examples related to the significance and application of a broad uncertainty framework – in this case relating to risk assessment and risk management in high-risk technologies.

What is uncertainty in relation to risk?

Uncertainty is a multifaceted issue. In general, we can say that uncertainty refers to knowledge being incomplete. Another broad understanding of uncertainty is ‘not knowing for sure’ due to a lack of information and/or ambiguous information (Grote, 2015). Uncertainty is also a term that stretches across a wide variety of disciplines, professions and problem domains (Smithson, 2008). Terms that have strong associations with uncertainty include ‘non-knowledge’, ‘ignorance’ and ‘negative knowledge’. Uncertainty does not have its own literature and is understood and described differently in different applications and contexts.

Within risk research, the classical and still majority view of uncertainty is to separate it from risk as something we cannot meaningfully calculate. Thus, uncertainty is referred to as events for which it is not possible to specify numerical probabilities. This definition of uncertainty can be traced back to the economist Frank Knight (Knight, 1921) who defined risks as measurable uncertainties: when they are too far from unmeasurable uncertainties, they are not uncertainties at all (Stirling, 2010). A more recent and similar definition is found in Kasperson (2008) where risk is associated to a context in which the magnitude of events and consequences are relatively well known whereas uncertainty refers to a context in which magnitude and probability cannot be estimated (Kasperson, 2008: 338).

More recently, broader approaches have been developing that view risk and uncertainty as interconnected, such as in Aven and Renn’s (2010: 3) definition of risk as ‘an event where the outcome is uncertainty’ or in concerns for the very rare ‘black swan’ events (Taleb, 2010). In these approaches, uncertainty becomes a more generic issue at the heart of risk (Grote, 2009, 2015). We can draw from this that an increasingly strong association between the two concepts is emerging in risk research. As a result, risk research can no longer be viewed as disentangled from concerns related to uncertainty. The risk field needs a broad framework for understanding uncertainty because the clear definitions and classic separation between risk and uncertainty have become imprecise and incomplete.

A significant issue for the assessment and management of risks in high-risk technologies is whether uncertainty is positive or negative. For example, in terms of nuclear power plants or airlines, is it good or bad to have uncertainties? Posing the question differently, in relation to the management of risks, is uncertainty essentially an adversary in the search for reliability and ‘safety’ or should risk management adopt a more varied approach, viewing some uncertainties as irreducible or even desirable in the search for improved technological services? A growing body of work has acknowledged that uncertainty plays a significant role in our understandings of safe and secure systems and societies (Grote, 2009, 2015; Taleb, 2010; Aven, 2014).

Proposing an integrative framework for risk management, Grote (2015) interestingly argues for the legitimacy of reducing, maintaining and increasing uncertainty as three different concepts within a comprehensive approach to risk management. She explains how the three options for managing uncertainty differ in their objectives, conceptual approach, control paradigm and measures. According to Grote, the risk management challenges made evident by the two major accidents of American space shuttles and, more recently, the Fukushima event.
illustrate the necessity for a comprehensive and more systemic management of uncertainty as part of risk management. She refers to how different concepts of risk control are associated with different professional cultures: engineers and executives believe in uncertainty reduction, operative personnel maintain uncertainty in the face of only partially controllable systems and, finally, social scientists are more open to adding uncertainty through learning and innovation. Grote warns that achieving a shared legitimacy of all three options will be difficult, and the criteria allowing decision makers to choose between one or all three of the options are challenging to develop.

**A structure for differentiating kinds of uncertainty**

Within risk research there are differences in how uncertainty is dealt with between disciplines and practice areas. For example, marked differences exist between qualitative and quantitative statistics-based approaches to uncertainty in risk assessments. Attempting to quantify numerical uncertainty is at the heart of statistical approaches – as Attewell (2008) describes: they attempt to ‘eat up’ uncertainty. By contrast, in the qualitative approaches associated with the social sciences, uncertainty is explored and described, giving particular attention to the gaps in what is known and providing explanations of what is not known, who does not know and why it is so.

Currently, no commonly accepted structure exists within which to discuss uncertainty within risk research; however, Bammer et al. (2008) bring together diverse perspectives on uncertainty, providing a comprehensive framework for thinking about uncertainty. They differentiate various types of uncertainty that can be associated with risk research (see Table 3.1). A first type is ‘what we know we do not know’. Bammer et al. (2008) describe known unknowns as the ignorance of which we are conscious.

<table>
<thead>
<tr>
<th>Meta-level</th>
<th>Known</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary level</td>
<td>Known knowns</td>
<td>Unknown unknowns</td>
</tr>
<tr>
<td></td>
<td>Known unknowns</td>
<td>Unknown unknowns</td>
</tr>
</tbody>
</table>

Adapted from Bammer et al., 2008.
craftsmanship provides an illustration of tacit knowledge in such organizations, where variance in actions to meet exceptional inputs combines conscious and unconscious knowledge (Pettersen and Schulman, 2015).

A third type of uncertainty is unknown unknowns, or meta-ignorance (Bammer et al., 2008). In this category, we only become aware of our ignorance in hindsight. Being an ‘unknown unknown’ is one of the requirements for what Taleb (2010) defines as ‘black swan events’, which are those macro events that continue to surprise us. Bammer et al. (2008) provide more prosaic examples of meta-ignorance, such as authors coming together to share different perspectives on a subject. Such examples also highlight that, although we only become aware of our own meta-ignorance in hindsight, it is relatively easy to spot other people’s meta-ignorance. Indeed, management of sociotechnical systems has long focused on revealing blind spots and challenging assumptions to uncover unknowns before they surprise us and lead to severe consequences (Lindaas and Pettersen, 2013). For example, the requirement to expand process variance in order to meet input variance has been described as ‘requisite variety’ (Weick, 1995).

**Abductive thinking and risk – exploring and increasing uncertainty**

A fundamental issue contributing to how uncertainty in a broad sense can be maintained and explored within risk research is abductive thinking (Weick, 2006; Pettersen, 2013). This approach, building on Charles Sanders Peirce’s3 concepts, has relevance for many aspects of risk analysis because it can be argued that these reasoning processes relate to knowledge development in assessments as well as management. Abductive thinking – namely, formulating explanatory hypotheses when uncertainty is pervasive – complements the idea of organizing to reduce uncertainty. In decision situations where uncertainty is important beyond problems associated with measurement, assigning probabilities to describe risk will have limited value and can even mislead the decision maker because the uncertainty and knowledge dimensions are not sufficiently reflected (Aven, 2014).

In research on operations within high-risk technologies, such as research on aircraft line maintenance (Pettersen, 2008; Pettersen et al., 2009), interpretations and actions that deviate from procedures and the system as designed are found to be an integral part of work, such as when performing diagnostic work to troubleshoot unexpected technical problems on an aircraft. Other comparable studies indicate that these tendencies are a more general characteristic of aircraft maintenance work (McDonald and Morrison, 2006a, 2006b; McDonald et al., 2009). Mumaw et al. (2000) have also documented similar findings from research on operators working in nuclear power plant control rooms. Such studies document that the system works well – not despite of, but because operators deviate from formal practice (Perin, 2005). These studies show the importance of including interpretive and dynamic approaches to risks, where uncertainty is systematically explored and sometimes even increased in response to inherent difficulties and complexities of work. As a principle of assessment, abductive thinking is complementary to the additive, linear, top-down logic of quantifying risk. For example, when maintenance technicians adjust their actions to the contingencies of a troubleshooting situation, they interpret a set of different clues to support which actions should be taken next. This process is very similar to that of scientists interpreting experimental results to evaluate a hypothesis. As in scientific enquiry, cultural and experiential knowledge is required when the technicians interpret the significance of evidence before actions are taken. In situations characterized by unpredictability and contingency, technicians ‘call on abduction’ in this way (Perin, 2005).
In a detailed analysis of Peirce's concept, Chiasson (2005) described abduction as the process of noticing an anomaly and pursuing an explanatory hunch. In this way, one brings a new idea (or hypothesis) up from the semi-conscious (e.g. tacit knowledge). This process starts, according to Chiasson, by noticing something surprising – an anomaly from the normal routine. This is followed by an individual and unregulated exploration, and finally the initial anomaly can be formulated into a plausible hypothesis. This can be shown as a three-step process:

1. A surprising fact is noticed.
2. An unfettered exploration of qualities and relationships is made.
3. Abductive reasoning is applied to make a guess that could explain the surprising fact (Chiasson, 2005).

Weick (2006) goes on to explain that the essence of abduction involves taking a fragment, such as an unexpectedly high temperature in a transformer, and then hypothesizing an ‘axis of meaning’ that suggests a world in which that discrepant temperature would be a meaningful symptom.

From this perspective, abduction is therefore a method of logic for addressing surprising (or anomalous) facts and exploring their qualities. Given a strong association between risk and uncertainty, abductive thinking provides a logical basis for how knowledge is produced to support risk analysis in situations where uncertainty is important. The resulting expression of risk can be acted on in different ways depending on the context. An abductive expression of risk is a theory and acknowledges uncertainty. It may even increase uncertainty by raising doubts related to a fact or a particular course of action.

Aven (2014) relates the logics of abduction to the application of risk assessment methods when uncertainty is pervasive. In his book *Risk, Surprises and Black Swans*, Aven (2014) describes how traditional perspectives on risk assessment dominate adaptive risk management contexts and uses probabilities to represent uncertainties, but that these are not particularly suited for situations where knowledge and uncertainty are crucial. Surprises always occur and Aven promotes a broad risk perspective where assessments must sufficiently reflect the knowledge and uncertainty dimensions. A Bayesian decision analysis is one methodology providing a strong theoretical framework for choosing the optimal decision but, according to Aven, in many cases it is difficult to use in practice. An alternative would be to have a procedural framework of decision rules based on assessment for different signal/warning levels that describes how to act in different situations. However, as previously described, even in comprehensively proceduralized systems such as aviation it is impossible to prescribe what to do in all situations. Risk analysis has to acknowledge the role of surprise; thus, a risk assessment will be relative to its position in time and space, and the risk assessor will have to be able to absorb and analyse relevant information as it develops. Aven relates abduction closely to a process of risk assessment. Through abduction, facts such as hazards are noticed and explored in relation to why they are present and how they can do harm. The thought process provides a hypothesis to explain the facts, and this gives suggestions as to what can be done to manage risk.

Introducing the notion of ‘speaking up’, Grote (2015) provides examples that illustrate how abductive logics can be applied in risk management situations. ‘Speaking up’ and communicating doubt about a course of action or suggesting new options to move forward is, according to Grote, crucial for risk management because it increases uncertainty by opening up new perspectives for decision making and action. However, Grote (2015) also warns that a heightened sense of uncertainty, related to both the people involved and the task at hand, is a reason for people to choose not to speak up.
Towards a broad uncertainty framework

Perspectives on how uncertainties associated with high-risk technologies should be managed are diverse; however, since the early 1980s, we seem to have been slowly moving out of what was two entrenched views. On the one side was a scientific focus on risk as the mastering of probabilities and a persuasion that this was the only ‘narrow’ solution for risk research and management advice. On the other, uncertainty was promoted as a conclusive argument for why successful system engineering and management was impossible and a reason for mitigating and stopping the development of high-risk technologies. Today, this is changing. Risk experts are increasingly paying attention to a wide variety of concepts and methods for understanding the role of uncertainty and dealing with incomplete knowledge in such technologies. From looking primarily at the role of experts and the possibility of scientific methods, research on technology and risk has made a move towards seeing risk assessments and risk management in an increasingly integrated perspective. This has led to a more equal partnership between the technical sciences and social sciences in approaches to uncertainty, where qualitative methods and the discovery of strengths and vulnerabilities in social structures, group dynamics and effects of power play an increasingly important part (Stirling, 2010).

The rationale – the age of high-risk technologies

Sociologist Charles Perrow’s (1984) groundbreaking analysis of structure in various systems is a relevant perspective for approaching issues of risk and uncertainty related to high-risk technologies. Perrow explains how uncertainty is not a characteristic of all high-risk technologies; for many, incomplete knowledge will always be an issue due to the information difficulties associated with the systems being interconnected and fundamentally complex in the way they operate. When viewed in relation to the potential for catastrophic consequences, Perrow concludes that, for some high-risk systems uncertainty can be accepted whereas for others considerable resources are required in order for systems to be sufficiently adaptable. Importantly, Perrow finds that a third category of high-risk technologies, including nuclear weapon systems and nuclear power, must not be used and developed further due to the combination of intrinsic information difficulties and their catastrophic potential (Perrow, 1984, 1999).

Following Perrow’s analysis, uncertainty will be a characteristic of managing the system in a number of high-risk technologies, including civil aviation and chemical industry. For these technologies, uncertainty must be challenged and management must be adaptable in order to achieve high reliability (LaPorte and Consolini, 1991). Of course, in some cases, where the intractability of uncertainty faces systems with potentially extreme consequences, the problems associated with uncertainty are broad and of a collective nature for society. Here uncertainty can be related to issues such as the justification of the technology connected to its future consequences or possibilities for reversibility. However, for all cases of high-risk systems characterized by interconnectivity and complexity, the problems associated with uncertainty also relate to risk assessment and management as part of managing the systems. It is the latter issues that will be the focus in the remaining sections of this chapter.

Applications of a broad uncertainty framework – some examples

Due to complexity and information difficulties, a classic focus on risk is an inadequate response to problems in high-risk technologies. Uncertainty cannot be approached only in a negative sense as something that should be avoided. Of course, this does not mean that someone can
foresee the unpredictable and prepare for uncertainty; however, a broader understanding of uncertainty shows that lessons have been learned and necessary alternatives to classic probability exist based on treatments of risk and uncertainty.

First of all, a broad framework does not require that traditional probability-based methods be discarded as irrelevant. On the contrary, expert-based judgements of probabilities and possible consequences, as well as quantitative cost-benefit analyses, are examples of methods that are still applicable for many problems. The design and management of high-risk technologies are organized around the imperative of results. Consequently, they are routine-seeking, developing techniques that are known to work and standardizing raw materials and other inputs in order to support system integration and the reliability of outputs. Here, classic approaches applying probabilistic techniques to assess risk have considerable contributions to make. In addition, in relation to the challenges inherent in assigning probabilities, research has emphasized methodological challenges of a quantitative nature and the possibilities of new types of scientific methods to analyse outcomes in complex systems in the face of uncertainty. Some civil aviation disasters are low probability but high consequence, making them rare events that are difficult to assess due to limited data from the past from which to draw (i.e. known unknowns in Table 3.1). Future events and associated consequences are often relatively poorly known, making probability distributions difficult to assign. Here, methods such as scenario analyses and considerations of sensitivity are being developed, thereby providing a range of different interpretations of what might happen (Stirling, 2010).

However, everyday imperatives to optimize processes and outputs also tend to direct attention towards simplifying advice and away from accepting uncertainty. For example, Wackers (2014) uses the notion of entrainment to describe how operations aboard the Snorre A oil platform in the North Sea become aligned with the corporate order to ‘deliver on production’, suppressing concerns for safety and over time developing patterns of work that blind people to the consequences of their actions. Wackers describes how the Snorre A case contributed to events that caused a major gas leak from the seafloor that came close to resulting in a catastrophic outcome. Wackers labels such entrainment as the social shaping of neglect of vulnerability (2014: 189).

High-risk technologies that achieve high levels of reliability, such as civil aviation, are often dominated by an integrated system perspective. The will to routinize also dominates here, making the system vulnerable to processes of entrainment, as with the case of Snorre A. However, in high-reliability organizations described among others in civil aviation, risk management also involves acknowledging the possibility of unforeseen circumstances and surprise (Pettersen and Aase, 2008; Pettersen and Bjørnskau, 2015; Pettersen and Schulman, 2015). Thus, the organizations that drive the efforts to routinize also demonstrate a great deal of variety in task performance (Perrow, 1970). The approach to structure in such organizations is therefore routine in one sense and flexible in another. The organizations improve and adapt to new evidence and novel situations based on the previous experiences and tacit knowledge of operational personnel (i.e. unknown knowns in Table 3.1). Elaborate meeting structures, systems and networks for knowledge sharing are also developed in these organizations to provide feedback, critique and integration of information across levels, both vertically and horizontally. Routines are also continuously evaluated based on the best available information.

As uncertainty changes (unknown unknowns in Table 3.1), for example due to system complexities that can cause unfamiliar interactions within a system, solutions change from issues of measurement and information management to issues of perspective and ways to apply plural perspectives to discover and deal with new situations. The importance of having a requisite variety of people within management and listening to diverse opinions in order to discover weak signals has been found as something that should be embraced as part of uncertainty management because it contributes to resilience. Some organizations, groups and operational personnel
have been found coping with uncertainty as part of their contributions to managing high-risk technologies (Weick et al., 1999). These approaches have been generalized in theories on managing the unexpected (Weick and Sutcliffe, 2001). By developing organizations that include perspectives and experiences that match the systems’ potential for surprises, the monitoring of the environment can improve in order to better identify early warnings and respond better to uncertainties as part of daily operations.

Conclusion
From the perspective of high-risk technologies, a key development for risk research is the development of a broader understanding of uncertainty where uncertainty is dealt with beyond expressions of probability. Tacit knowledge and meta-uncertainty are types of unknowns where probability-based approaches are of limited use; however, both are relevant and part of risk assessment and risk management in high-risk technologies. Such recognitions are shaping an approach to risk research that utilizes a range of methods that are effective in accepting the uncertainty of hazards, threats, surprises and the unforeseen (Aven, 2014; Grote, 2015). This implicates a broader framework of concepts, theories and methods, which includes but also moves beyond approaches in which risk is presumed to be manageable through scientific methods. A broad approach to uncertainty acknowledges both analytical- and experience-based assessments whilst also including social science theories of safety and reliability as well as theories addressing characteristics of decision making under uncertainty such as power issues.

This chapter has proposed abductive thinking as a fundamental issue for risk research. Of course, abductive thinking does not mean that one can foresee the unpredictable, and in many situations it might make information about what could happen more complicated or result in flawed hypotheses. High-risk technologies do, however, continue to arise with unwanted surprises, such as the disappearance of Malaysian Airlines flight MH370 in 2014, demonstrating that such technologies require the continuous exploration of uncertainty.

No general agreement exists within risk research as to whether uncertainty can be reduced or if it is inevitable. This variation in approaches to uncertainty can result in quite polarized debates, such as those related to risk assessment in which risk professionals debate the very nature of risks (Quiggin, 2008; Aven and Renn, 2010). Are knowledge constructs of risks created by someone and selected under the influence of some social values, making uncertainty fundamentally irreducible? Or are risks ‘objective’ and value-free scientific facts, where uncertainties can be tamed by systematic reasoning? These debates seem to have lessened recently due to conceptual frameworks that bridge the divide (Rosa, 1998; Renn, 2008; Aven and Renn, 2010) and assessments being more balanced in practice (Aven and Renn, 2010).

Acknowledgements
This research was supported by The Norwegian Research Council TRANSIKK program. I would like to thank Gudela Grote and Ole A. Lindaas for their insightful comments on an earlier version of the manuscript.

Note
1 Charles Sanders Peirce (1839–1914) was an American philosopher, logician and scientist. Today, he is primarily known as the founder of pragmatism and as the developer of a fertile theory of signs and sign-action (Bergman and Paavola, 2014). However, he is also recognized as a central figure in modern logic and the methodology of science. In Peirce’s work, abduction refers to a distinct form of logical inference.
References


Kenneth Pettersen


