Risk Analysis, Vol. 40, No. 10, 2020 DOI: 10.1111/risa.13549

Perspective

Risk Science Contributions: Three Illustrating Examples

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ABSTRACT: This article aims to demonstrate that *risk science* is important for society, industry and all of us. Rather few people today, including scientists and managers, are familiar with what this science is about—its foundation and main features—and how it is used to gain knowledge and improve communication and decision making in real-life situations. The article seeks to meet this challenge, by presenting three examples, showing how risk science works to gain new generic, fundamental knowledge on risk concepts, principles, and methods, as well as supporting the practical tackling of actual risk problems.

KEY WORDS: Precautionary principle; risk science; smoking risk

1. INTRODUCTION

The Society for Risk Analysis (SRA) has recently developed a strategic plan that includes a vision statement, expressing that the society is "the world's leading authority on risk science and its applications" (SRA, 2019). The scope and pillars of this science are explained in some related SRA documents (SRA, 2017a, 2017b). Following Hansson (2013), risk science can be seen as the practice that provides us with the most warranted statements (most justified beliefs) that can be made at the time on subject matters covered by the risk field. This field captures scientific journals, scientific conferences, researchers, research groups and societies, educational programs, etc., on risk-related topics, including the understanding, assessment, characterization, perception, communication, management, and governance of risk. In line with this thinking, knowledge refers to "justified beliefs," and scientific knowledge to the "most justified beliefs." The present article looks closer into what this science is about and discusses why this science is important.

Simplified, the risk science can be viewed as comprising two main components. The first one is to support scientific knowledge generation for specific activities, for example when studying risk related to climate change. The scientific work is typically multidisciplinary or interdisciplinary, building on competences from various fields and sciences, including risk science. In the case of climate change risk, other sciences (particularly natural sciences) play the dominant role, with risk science supporting the research by providing guidance on, for example, how to best characterize the climate change risk. The risk science contribution is referred to as applied risk science (type A risk science); refer to SRA (2017a, 2017b).

The second risk science component is the generic, fundamental risk science, referred to as type B. It covers scientific knowledge related to the development of concepts, principles, approaches, methods, and models for understanding, assessing, characterizing, communicating, managing, and governing risk. When publishing a paper on how to best characterize risk, a contribution is made to generic risk science. Developments in generic risk science support the applied risk science by offering improved concepts, principles, etc., for practical use. Applied risk research can point to basic challenges related to understanding, assessing, communicating or managing risk and, in this way, stimulate generic risk science. It can also lead to new generic knowledge, in some cases. An example is nuclear risk assessments, which

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The copyright line for this article was changed on 13 July 2020 after original online publication.

0272-4332/20/0100-1889$22.00/1

have contributed to improved generic risk assessment approaches and methods (NRC, 1975; Rechard, 1999, 2000). Thus, there is a close interaction between generic and applied risk science, as is the case for other disciplines where this distinction applies (e.g., statistics).

In the literature, it is common to distinguish between theoretical/pure/fundamental sciences on the one hand and applied sciences on the other, covering basically the same ideas as used for defining generic and applied risk science. The word "generic" is highlighted here as the B knowledge is relevant for different types of applications, and "theories" can be seen as a too narrow term to explain the development of concepts, principles, approaches, methods, and models for understanding, assessing, characterizing, communicating, managing, and governing risk. For example, research focusing on developing a general, practical procedure for evaluating the quality of performed risk assessments, can be classified as generic, but not so much as theoretical.

For the proper understanding of this science, it is essential to see the difference between the risk science and a specific risk analysis or risk assessment. A risk assessment is a method for assessing risk and conducting the assessment can produce scientific risk knowledge about a specific activity—it is used for type A risk knowledge generation, for example to improve our understanding about climate change risk. The type B type of risk science knowledge comes into play when researching possible improvements in the risk assessment method, for example by identifying new ways of presenting the uncertainties associated with the results.

Today there are a number of journals, conferences, academic positions, research and study programs, societies, etc., on risk-related topics worldwide, both generic and applied. Yet risk science is not broadly acknowledged as a distinct science. A good illustration of this is classifications of scientific areas, as used for example in research funding schemes, where risk science is not included (Hansson & Aven 2014). In recent years, considerable work has been conducted to clarify the scope and foundation of the risk science (e.g., SRA, 2015a, 2015b, 2017a, 2017b; Aven, 2018a,b; 2020a), but communication concerning this issue at scientific conferences and in various risk societies (such as SRA and ESRA—European Safety and Reliability Association) has convinced the present author that more work is needed to explain what this science is about and what it adds, compared to other disciplines. Theoretical work highlighting rationale and argumentation is important, but often concrete examples can be more informative and convincing.

The present article follows up this idea and presents three examples, showing how risk science works and what its contribution is. As such, the article contributes to scientific knowledge generation, by pointing to and arguing for what are the "most justified beliefs" of the risk field in relation to the cases considered. The examples cover both generic and applied risk science. The first example is generic and concerns the precautionary principle, which has been subject to intense discussions over several decades. The two last examples are applied, the second discussing risk related to smoking, a case where we have access to a lot of data, whereas the third example addresses space exploration, where little data are available and the assessments need to be based on modeling and testing of the systems studied.

A main reference for concluding what is the current state of the art of the risk science is the SRA documents referred to above (SRA, 2015a, 2015b, 2017a, 2017b). These documents have been developed by a broad group of senior risk scientists, with input from members of the society. When discussing what is scientific knowledge—the most justified beliefs of the field—there is clearly an element of subjectivity involved. This is acknowledged. The key is the arguments put forward, which are open for critique and discussion, which in their turn can lead to further analysis and new risk science knowledge.

2. EXAMPLE 1: THE UNDERSTANDING AND USE OF THE PRECAUTIONARY PRINCIPLE

The precautionary principle emerged as a concept in the 1970s–1980s in German environmental law, and it was incorporated into international law following the North Sea Conference on the Protection of the North Sea (NSC, 1987). In the declaration from this conference, we can read:

> Accepting that, in order to protect the North Sea from possibly damaging effects of the most dangerous substances, a precautionary approach is necessary which may require action to control inputs of such substances even before a causal link has been established by absolutely clear scientific evidence. (NSC, 1987)

We find a similar formulation in the well-known 1992 Rio Declaration (Freestone & Hey, 1996):

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

Since then, the principle has permeated most international environmental conventions, and the principle is also a cornerstone of the European Union's (EU) regulations and law, stating that regulatory actions may be taken in situations where potentially hazardous agents might induce harm to humans or the environment, even if conclusive evidence about the potential harmful effects is not (yet) available (EU, 2002; Science for Environment Policy, 2017).

Real-life situations created a need for a principle to protect values (related to the environment and humans' health and lives) in the face of uncertainties and risks. The formulation of this principle was, however, not straightforward; it has created debate and still does. Some of the issues discussed are:

- What are the criteria for invoking the principle? When do we have "scientific uncertainties"?
- Is the idea adequately reflected by a "principle"? Is the precautionary principle a decision rule? A decision rule can be seen as a logical statement of the type "if (condition), then (decision)". As formulated by Peterson (2007), "A decision rule simply tells decisionmakers what to do, given what they believe about a particular problem and what they seek to achieve."
  Is the principle irrational in the sense that it leads to inconsistent decisions?
- Does the principle promote a risk-averse attitude, hampering development and innovation?

Risk science has now discussed these issues for over 30 years, as generic risk science issues, as well as applied risk science. The applied part relates to the challenges of using the precautionary principle in specific settings, for example implementing the principle in EU regulations and law on or related to, for example, climate change, food, and/or chemicals.

The discussion in this article focuses on the generic, fundamental risk science. Considerable work has been conducted to clarify the meaning of the principle. The scientific literature includes, for example, many definitions of the principle beyond those referred to above. At any point in time, there can be a discussion on what are the most warranted judgments (most justified beliefs) on this topic. As mentioned in the introduction section, a key reference in this article is the work conducted by SRA. Here, two definitions of the principle are highlighted (SRA, 2015a):

- An ethical principle expressing that if the consequences of an activity could be serious and subject to scientific uncertainties, then precautionary measures should be taken, or the activity should not be carried out.
- A principle expressing that regulatory actions may be taken in situations where potentially hazardous agents might induce harm to humans or the environment, even if conclusive evidence about the potential harmful effects is not (yet) available.

The SRA documents do not, however, explain what "scientific uncertainty" and related statements like "conclusive evidence not yet available" mean in this setting. The issues have been subject to considerable discussion in the literature; see for example Aven (2011), Cox (2011), North (2011), Vlek (2011), Sandin (1999), and Stirling (1998, 2007). Based on current knowledge, the present author will argue that it is sensible to relate scientific uncertainties to the difficulty of establishing an accurate prediction model for the consequences considered (Aven, 2011). If such a model cannot be established, the precautionary principle can be invoked. Following this thinking, it is clear that the principle is not to be interpreted as a decision rule but as a guiding perspective for risk handling, a perspective which is considered expedient, prudent, or advantageous (Aven, 2020a, p. 179). Judgments are needed to decide when the uncertainties are scientific and the principle can be invoked.

Risk scientists have performed detailed studies of the case that a decision rule-based interpretation of the principle is adopted. It is shown, for example, that the use of the principle in this case leads to inconsistencies (Peterson, 2006, 2017; Stefánsson 2019). However, recent work points to the fact that the conditions applied to ensure these results are founded on comparisons of likelihood judgments (Aven, 2019a, 2020a). For example, one such condition states that "If one act is more likely to give rise to a fatal outcome than another, then the latter should be preferred to the former, given that both fatal outcomes are equally undesirable" (Peterson, 2006). However, in the case of large uncertainties, such judgments cannot be justified. An assessor (which could be the decisionmaker) may judge an event A to be more likely than an event B, but the decisionmaker should not give much weight to this when the judgment has a poor basis. See also, discussion in Boyer-Kassem (2017a, 2017b).

We see how risk science discussions lead to new knowledge concerning the understanding of the principle. Considerable criticism has been raised against the principle, and this has led to further discussion and new insights. A good example, in addition to those mentioned above, is the work by Sandin, Peterson, Hansson, Rudén, and Juthe (2002), which defends the precautionary principle against five specified charges. One of these charges is that the principle marginalizes science. As discussed by Sandin et al. (2002), see also Aven (2011), this charge can be rather easily refuted. The point is that, for the situations addressed, science is not able to provide clear answers because of the scientific uncertainties. The principle is to be considered a risk management strategy in the case of weak knowledge about the activities considered, for example generated by the operation or use of a specific system or product. The measures to be taken could include holding back the activity until more scientific knowledge is available. As such, the principle stimulates science and scientific work rather than marginalizing it.

If a company would like to introduce a new product into the market, the basic idea of the precautionary principle is that the company has the burden of proof, showing that the product is safe and the negative risks associated with its use are acceptable. Risk science provides knowledge about how to make judgments about what is safe and acceptable risk in such a context. Probability theory and Bayesian analysis are shown to be useful instruments in this regard, by calculating the probability of the product having hazardous effects given all available evidence (Bernardo & Smith 1994; Meeker & Escobar 1998). Acceptance of the product can only be given if this probability is small and the evidence strong.

Risk science shows how these ideas relate to fundamental theory of statistical inference and hypothesis testing. According to this theory, the null hypothesis is that the product is acceptable and strong evidence must be provided to show harmfulness, to get the product restricted. Attention is mainly paid to the error of type I: to wrongly reject a true null hypothesis, that is, to conclude that the product is hazardous when that is in fact not the case. However, following precautionary thinking, considerable weight also has to be placed on the error of type II: to not conclude that the product is hazardous when that is actually the situation. Adopting a strict precautionary approach, there is initially "a red light which is only switched to green when there is convincing evidence of harmlessness" (Trouwborst, 2016). The burden of proof is reversed. The traditional perspective stresses the costs (interpreted in a wide sense) of erroneously taken protective measures, whereas the precautionary perspective stresses the costs of an erroneous lack of protective measures. Risk science discusses the tensions and need for balance between these two concerns. There is no scientific optimal formula. The issue is mainly about values, priorities, ethics, management, and politics. It is about balancing development and protection. Too much protection hampers development and vice versa. The result is a difference between different political parties, countries, and cultures; see discussions in HSE UK (2001), Sunstein (2005), Wilson et al. (2006), and Wiener and Rogers (2002).

Risk science provides knowledge about aspects to consider when finding this balance, and what principles, approaches, and methods can be used to support the communication and decision making. Extensive theories exist for this purpose, such as decision analysis (e.g., Howard & Abbas 2015; Lindley, 1985). Risk science explains that some principles, approaches, and methods favor protection, others development. The precautionary principle belongs to the former category, whereas cost-benefit type of analysis supports the latter with its expected value focus, placing little weight on uncertainties and risks (e.g. Aven & Renn, 2018).

Risk science clarifies and explains what risk is and the challenges related to measuring its magnitude when the activities considered are subject to large uncertainties—allimportant knowledge for understanding the rationale for the precautionary principle. There is no way to calculate meaningful risk numbers in this type of situation—obviating the precautionary principle.

Risk science also shows the link to risk perception. From perspectives in the 1980s and 1990s, in which professional risk judgments and risk perception were basically considered the same (Beck, 1992; Douglas & Wildavsky, 1982; Jasanoff, 1999; Wynne, 1992), the risk science of today is built on risk concepts and frameworks that provide clear separations between professional judgments of uncertainties and risks, and what are perceptional aspects like fear and dread. When laypeople found the nuclear risk unacceptable in the 1980s and 1990s, experts pointed to these people being strongly affected by risk perception and feelings. The founding idea was that risk could be adequately reflected by probabilities and numbers, expressing the truth about risk. Today's risk knowledge has rejected this perspective (Aven & Renn, 2018; SRA, 2017b); it highlights the fact that uncertainty is a main component of risk, and, to understand people's reaction to a hazardous activity, it is essential to acknowledge that people's risk perception is not only about feelings but may also capture conscious judgments of uncertainties that are, to a varying degree, reflected by the professional risk judgments. What is a sufficient level of scientific uncertainties for invoking the precautionary principle can be strongly influenced by laypeople's perceptions. Climate change uncertainties and risk are a good illustration.

Risk science also points to the need to distinguish between the precautionary principle characterized by scientific uncertainties, and the cautionary principle where the uncertainties are not necessarily scientific (Aven, 2019b). In many situations, we face risk and uncertainties, but the phenomena studied are well known. The uncertainties are not scientific, yet protection is a major concern, as discussed above. An example is the German decision to phase out their nuclear power plants by the end of 2022, following the 2011 Fukushima nuclear disaster (Ethik-Kommission, 2011). Judgments were made that the risks were unacceptable. Weight was given to the cautionary principle (Aven & Renn 2018).

3. EXAMPLE 2: IS SMOKING AND PASSIVE SMOKING DANGEROUS (RISKY)

This second example provides an illustration of applied risk science: How does risk science contribute to the issue of understanding the risks related to smoking?

Today, there is broad agreement in society and among scientists that smoking is risky; however, it is not that many years since the statement that smoking is dangerous was very much contested. In 1960, a survey by the American Cancer Society found that not more than a third of all US doctors agreed that cigarette smoking was to be considered "a major cause of lung cancer" (Proctor, 2011). As late as 2011, research work conducted by the International Tobacco Control Policy Evaluation Project in The Netherlands showed that only 61% of Dutch adults agreed that cigarette smoke endangered nonsmokers (Proctor, 2011; Willemsen et al., 2011).

The main sciences dealing with this issue are the medical and health sciences. Risk science and statistics have supporting roles, providing knowledge on what it means that smoking is dangerous or risky, that smoking causes lung cancer, and how assessments should be conducted to conclude on such questions, taking into account all types of uncertainties. Risk science and statistics provide guidance on how to balance the two main concerns: the need to show confidence by drawing some clear conclusion (expressing that smoking is dangerous) and to be humble by reflecting uncertainties.

Standard statistical and risk analysis frameworks are used for these purposes, established by statistics and risk science. For example, a probability model may be introduced based on frequentist probabilities, expressing proportions of persons belonging to specific populations (e.g., men of a specific age group) that get lung cancer. By comparing the probability estimates for nonsmokers and for smokers, and introducing parameters representing, for example, the number of cigarettes per day and the duration of smoking, conclusions can be made, for instance, that smoking significantly increases the chances of getting lung cancer, where chance is understood in a frequency way. In this framework, concepts like variance and confidence intervals are used to characterize the uncertainties. Flanders, Lally, Zhu, Henley, and Thun (2003) and Yamaguchi, Kobayashi, and Utsunomiya (2000) provide two examples demonstrating this type of framework and analysis.

Another common framework is the Bayesian one, in which epistemic uncertainties are represented by so-called knowledge-based or subjective probabilities expressing degrees of beliefs. When new evidence becomes available, the probabilities are updated, using Bayes' formula. A key quantity computed in this setup is the change in the probability that a person will get cancer when changing the number of cigarettes per day and other parameters.

Statistical and risk science research evaluates these frameworks and methods, with the aim of improving them. As we know, the standard statistical frameworks have limitations; they cannot provide strict proof. They can demonstrate correlation but not causality. This has of course been used by the cigarette manufacturers, who have disputed any evidence supporting the conclusion that smoking is dangerous. As indicated above, it has taken a long time to convince people that smoking kills. In some countries, the severe consequences of smoking have still not been acknowledged.

The challenge is to distinguish causality from correlation. The issue is a fundamental one in science. It is easier to disprove causality than to prove it (refer to Karl Popper's falsification theory). Statistics and risk science provide relevant knowledge and research. As a result of this research, there are now many methods available that can be used to study causality and, in particular, to analyze how changes are propagated through systems and how changes in the input lead to changes in the output (Aven, 2020a; Cox, Popken, & Sun, 2018, p. 112).

The medical and health research conclusions concerning passive smoking are similar: passive smoking leads to an increasing risk related to many diseases or health problems, especially diseases in children, and cancers (Cao, Yang, Gan, & Lu, 2015). Statistics and risk science provide input to these conclusions, as described above.

The societal implications of the above research vary from country to country. However, we see an increasing trend of governmental interventions and regulations to stop individuals from smoking, particularly in specified places. Risk science provides input to this type of discussion. An example related to passive smoking is presented in Aven and Renn (2018). Reference is made to a study in the UK that questioned the rationale for banning smoking in public places (Committee on Economic Affairs, 2006). The study indicated such banning would represent a disproportionate response to a relatively minor health concern. The approach taken was a standard cost-benefit type of reasoning. Risk science provides arguments for seeing beyond this framework, which ignores many aspects of risk and uncertainties, as discussed by Aven and Renn (2018).

4. EXAMPLE 3: SPACE EXPLORATION

Consider the problem of assessing and managing the risk for a spacecraft with a specific mission. To be concrete, think about the Apollo or Shuttle projects and the current plans for sending people to Mars. When preparing for such flights, risk considerations play an important role. Risk science offers guidance on how to think in relation to risk and how to best assess, communicate, and manage the various risks. The problems are fundamentally different from those discussed in the previous section, as relevant data and statistics are not available. Alternative analysis approaches and methods are needed. Basically, risk science offers three types of perspectives: quantitative, qualitative, and a mixture (semiquantitative), all based on models to represent the system and related processes. Models are needed, as experience in the form of observations of the performance of the spacecraft is not available in the planning phase.

It is interesting to note that quantitative, probabilistic risk analysis (PRA) was used in Apollo, but it was not continued (Paté-Cornell & Dillon, 2001). The Shuttle was designed without PRA; instead, qualitative approaches like failure mode and failure effect analysis (FMEA) were used. In relation to the Apollo PRAs, considerable focus was on the numbers calculated. A probability of success in landing a man on the moon and returning him safely to earth at below 5% was indicated (Bell & Esch 2018; Jones, 2019). For the NASA management, this number was considered dramatic and harmful for the project: It would be impossible to communicate to society a risk of that magnitude. The result was that, in relation to the Shuttle project, they later stayed away from PRAs as a design tool. The judgment was that PRAs overestimated the real risk. The result of the high-judged risk numbers in relation to Apollo was that the risk in that project was acknowledged as a serious problem, and measures were implemented to make improvements in all aspects of the project and design.

NASA management believed and testified to Congress that the Shuttle was very safe, referring to a 1 in 100,000 probability of an accident (Jones, 2019). The justification for this number was, however, weak. NASA engineers argued for 1 in 100 and, following the loss of Challenger and more detailed assessments, the latter number was used.

Risk science at that time provided guidance on how to conduct the PRAs. These analyses are quantitative, with probabilities computed for different types of failure events and effects using event trees and fault trees. An equally important value of the PRA as the quantification is the improved understanding of the system and its vulnerabilities (Apostolakis, 2004). The systematic processes of a PRA require that the analysts study the interactions of subsystems and components and reveal common-cause failures. Risk science provides guidance on how to best do this.

This case demonstrates the challenges of using numbers to characterize risk. At the time of Apollo, risk analysis was very much about PRAs and quantification of risk using probabilities. Although the importance of gaining system insights was highlighted as mentioned above, the numbers were considered the main product of the analysis, estimating the real risk level. The main goal of the risk analysis was to accurately estimate risk. If a failure probability of 0.95 was computed, it was interpreted as expressing the frequency of failures occurring when making a thought-construction of many similar systems. Clearly, if such a frequency represented the true failure fraction, the project would not be able to continue—it would have been too risky. Risk science explains, however, that this number does not express the truth or what will happen in the future, but is a judgment based on modeling and analysis, which could be supported by more or less strong knowledge. The actual frequency could deviate strongly from the one estimated or predicted. In this case, the knowledge basis was obviously weak, and the numbers should therefore not be given much weight. The fact that the analysis was also based on many conservative assumptions, leading to higher risk numbers than the "best estimates," provided additional arguments for not founding the risk management only on the numbers.

At the time of these projects, a main thesis of risk science was that risk can be adequately described by probability numbers. More precisely, risk could be well characterized by the risk triplet, as defined by Kaplan and Garrick (1981), covering events/scenarios, their consequences, and associated probability, answering the following three questions:

- What can happen? (i.e., What can go wrong?)
- If it does happen, what are the consequences?
- How likely is it that these events/scenarios will occur?

This perspective on risk is also commonly used today, but new knowledge has been derived since the 1980s. According to contemporary risk science, it is essential that the risk characterizations also cover the knowledge supporting these probabilities and judgments of the strength of this knowledge (SRA, 2017b). Of special importance here is the need to examine the assumptions that the probabilities are based on, as they could conceal aspects of risk and uncertainties and reveal potential surprises relative to the knowledge that the assessment is based on. The main aim of the risk assessment is not to accurately estimate the "true" risk but to understand the risk and characterize it reflecting the knowledge available.

Reference is made to Aven (2020b) for a thorough comparison of risk science of the 1980–1990s and today, particularly on the issue of risk characterizations. Fundamental works by Apostolakis (1990), Paté-Cornell (1996), and Kaplan and Garrick (1981) are reviewed. Aven (2020b) also discusses the use of conservatism in risk assessments—replacing uncertain quantities with values that lead to a higher level of risk. This is a common practice in risk assessments, but risk science has provided strong arguments against its use; see discussion in Paté-Cornell (1996) and Aven (2016).

Another topic that should be highlighted here is approaches and methods for sensitivity and importance analysis, which provide insights about what are the most critical elements of the problem discussed, see for example Helton and Davis (2002), Saltelli, (2002), and Borgonovo (2006). A continuous research has been and is conducted to enhance the approaches and methods used for this purpose, building on basic ideas from the 1970–1980s.

NASA (Jones, 2019) makes some interesting statements concerning the importance of risk analysis:

> Shuttle was designed without using risk analysis, under the assumption that good engineering would make it very safe. This approach led to an unnecessarily risky design, which directly led to the Shuttle tragedies. Although the Challenger disaster was directly due to a mistaken launch decision, it might have been avoided by a safer design. The ultimate cause of the Shuttle tragedies was the Apollo era decision to abandon risk analysis .... The amazingly favorable safety record of Apollo led to overconfidence, ignoring risk, and inevitable disasters in Shuttle. ... The Shuttle was cancelled after the space station was completed because of its high risk. NASA's latest Apollo like designs directly reverse the risky choices of Shuttle. The crew capsule with heat shield is placed above the rockets and a launch abort system will be provided. (Jones, 2019)

According to NASA, the experience with the Apollo and Shuttle projects suggests two observations:

> First, the most important thing is the organization's attention to risk. To achieve high reliability and safety, risk must always be a prime concern. Second, the risk to safety must be considered and minimized as far as possible at every step of a program, through mission planning, systems design, testing, and operations. (Jones, 2019)

The message is clearly that what is needed is proper risk management and a good safety and risk culture. The investigations following the Shuttle disasters found a bad safety culture, leading to poor decisions. Risk assessments, like PRAs, are useful tools but alone will not help much if the culture and the leaders are not encouraging scrutiny and follow up of all types of issues, to enhance reliability and safety.

Risk science provides the concepts, principles, methods, and models for understanding what proper risk management and a good safety and risk culture mean, and how this can be best achieved. NASA has itself contributed to such knowledge through considerable work on these issues over many years (see e.g., NASA, 2019). NASA has also developed and motived research on specific risk assessment models to support decision making in space mission planning and design, see for example Borgonovo and Smith (2011).

Jones (2019) gives a simple illustrative example, showing the importance of proper risk assessment and management. A mission is often thought of as a chain of links, and success is believed to be ensured by giving priority to the weakest links, and improving others is considered wasted effort. However, such reasoning could be disastrous, as the overall probability of failure is basically determined by the sum of all the linked failure probabilities. With many links, the overall failure probability could be high, even if each one of the linked failure probabilities is small. The risk management needs to take this into account when seeking to control and reduce risk. Risk analysis and risk science provide this type of knowledge. They specifically help the decision makers to use the organization resources in the best possible way. If a big risk for one link is difficult and expensive to reduce, the same total risk effect could be achieved by improving a set of other links.

There is of course no guarantee that applying today's risk science would avoid future space disasters. However, the knowledge gained provides an improved basis for understanding, assessment, communication, and management of the risks involved in such activities. It is a challenge to ensure that this knowledge is present in the organization. How to ensure this is in itself an issue of risk science, and much can be done to be successful in this respect. We will discuss this in more detail in the next section.

5. DISCUSSION

As illustrated by these three examples, risk science provides guidance on concepts, principles, methods, and models for how to understand, assess, characterize, communicate, and manage (in a wide sense) risk. No other sciences have this scope. As with statistics, there is a generic, fundamental part and an applied part. Statistics is the science about collecting, analyzing, presenting, and interpreting data. The second example, of smoking, shows that statistics support risk and health sciences. Many aspects of risk can be suitably handled within a statistical framework, but not all. Proper risk assessment and management require considerations that extend beyond data, as clearly demonstrated, for example, by the discussion of the precautionary principle in Section 2. Risk science builds on a number of fields and sciences in the same way as statistics, including mathematics, uncertainty analysis, operations research, and management science. Regarding the applied part, risk science supports other sciences, like natural science, as discussed in Section 1 and illustrated by the smoking example in Section 3.

There are considerable overlaps between different sciences, and there is a continuous debate about what are the proper structures and names for different types of fields and disciplines. For example, does risk science include uncertainty science or vice versa? In general, we can say that risk science has a focus on future events and consequences, and related models and parameters, whereas uncertainty science is concerned about any type of quantities, whether related to the future, present, or the past. The examples presented in the previous sections encourage the use of a unified perspective, a risk and uncertainty science. The point being made is that since uncertainty is a key aspect of risk, uncertainty science provides essential input to risk science. The smoking example shows that risk considerations are not only about uncertainties as such but equally about the consequences of the activities—the severity of the consequences: the implications. In practice, such considerations could also be included in uncertainty science, and we are led to similar scopes for these fields.

The risk and uncertainty sciences are rather small compared to, for example, statistics, at least if we compare the number of academic positions and study programs founded on the generic parts of the sciences. Unifying the risk and uncertainty sciences is therefore a sensible strategy, if broad acknowledgment is to be obtained. The examples presented in this article can be seen as illustrations of the risk and uncertainty science, defined as the science that produces knowledge on how to understand, assess, communicate, and manage (in a wide sense) risk and uncertainties. As in risk analysis, there are different perspectives in uncertainty analysis. A common perspective often referred to in uncertainty analysis is the Knightian framework, in which risk is limited to situations where objective probabilities exist (Knight, 1921; Stirling, 2007). This framework has been strongly criticized in the literature, as the definitions are based on too narrow interpretations of risk, compared to daily uses of this concept and the practice and sciences associated with risk (see e.g., Aven, 2010). If we relate this framework to the three examples studied in the present article, we can quickly conclude that, if we were to adopt the Knightian terminology, we could not speak about risk in relation to situations where the precautionary principle applies or in relation to space projects. The framework is clearly not in line with the use of risk science in this article and cannot be used, if a unified risk-uncertainty science is to be developed and advocated. Only in the smoking example can arguments be provided for referring to risk, if the Knightian framework were to be adopted.

Within all sciences, there is a "battle" between different schools and perspectives, on what represents the most warranted statements—justified beliefs—of the fields. Such is also the case for risk science. Not all risk scholars will agree on the argumentation used and conclusions made in the previous sections when referring to the current risk science. For risk science, there has been a lack of institutions and societies willing to draw the necessary conclusions. An exception is the SRA, which has recently produced several fundamental guidance documents (SRA, 2015a, 2015b, 2017a, 2017b). It can be argued that the standardization organizations (like International Organization for Standardization) also produce such statements and beliefs, but these organizations are not science-based, as discussed by Aven and Ylönen (2019) and can therefore not be said to reflect the most warranted or justified beliefs of the scientific field.

Risk science is using different types of research, as described in Aven (2018b), both empirical and conceptual. Example 1 on the precautionary principle is very much an illustration of conceptual research, whereas Example 2 is mainly empirical. Example 3 addresses conceptual issues when discussing how to best assess and characterize the risk, but it is empirical and applied, in the sense that it specifically addresses the NASA spacecraft.

In SRA (2017a, 2017b), different topics of risk sciences are identified and described. A specific topic relates to solving practical risk problems. It captures the links and interactions between generic risk science and applied risk science. A number of issues are discussed in these SRA documents, and a further development has recently been presented—a document covering a number of tests to be used to evaluate the quality of risk analyses supporting risk management decisions (ARMSG, 2019). These tests were assembled by a group of experienced risk analysts, focusing on their experiences with pitfalls and shortcomings they have observed in practice. The document represents risk science guidance, of importance for assessing and managing risk for situations such as those discussed for the spacecraft systems in Example 3.

6. CONCLUSIONS

This article has presented three examples, with the aim of demonstrating that *risk science* is important for society, industry, and all of us, by providing knowledge on concepts, principles, methods, and models and improving communication and decision making in real-life situations. Example 1 highlights the precautionary principle and shows how generic, fundamental risk science contributes to developing this principle, clarifying its meaning and helping authorities and others to make proper use of it in practice. Example 2 shows that risk science together with statistics provides support for how to be able to conclude on whether smoking is dangerous. Finally, Example 3 reviews the NASA Apollo and Shuttle spacecraft and shows how risk science and lack of risk science had serious implications for the risk management, communication, and decision making of NASA.

Risk science is a young science, and its scope and foundation are emerging. Examples showing key features of this science are considered important for its development. The three examples in the article provide insights into what risk science means and how it works in practice, covering both generic risk science and applied risk science. For the further development and recognition of risk science, there is a need for relevant societies and organizations like SRA to initiate strategic processes for strengthening the links to other related fields and sciences, particularly on uncertainty analysis and management. A unified risk and uncertainty science is more likely to be broadly accepted as a distinct science than both separately.

ACKNOWLEDGMENT

The author is grateful to two reviewers for their useful comments and suggestions to the original version of this article.

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