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The reliability science: Its foundation and link to risk science and other sciences

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A B S T R A C T

Several authors have recently questioned whether reliability is a science and a new science. The current paper follows up this discussion. It is argued that reliability is indeed a science and it is important that it is broadly acknowledged as such. This science is defined as the practice that provides us with the most warranted statements (justified beliefs) that are made by the reliability field or discipline; it covers concepts, theories, principles, approaches, methods and models for understanding, assessing, characterizing, communicating and managing reliability, with applications. The key pillars for this science are outlined. It is argued that reliability science can be viewed as a special case of risk science. Links to other sciences, like probability and statistics, are also discussed.

1. Introduction

At the 10th International Conference on Mathematical Methods in Reliability, MMR2017, a number of reliability scholars discussed "Is reliability a new science?" [1, 32, 34, 44]. Here, the term 'reliability' refers to reliability theory and practice. The starting point for the discussion was work by Paolo Rocchi on the topic [30, 31]. Some of the discussants (mainly Singpurwalla) argued that reliability is not a science, rather it is an essential technology, useful and valuable, applying science to facilitate decision making. Their reference is mainly natural sciences, and mathematics and statistics are also rejected as distinct sciences. Mathematics and probability theory can be viewed as a language of science, whereas statistics is seen as an enabler and a technology of science, like engineering. Others highlight that the above conclusions depend on the definition and understanding of the science concept. Anderson-Cook [1] makes this point clear when referring to the Oxford English Dictionary definition of science, stating that science is "the intellectual and practical activity encompassing the systematic study of the structure and behavior of the physical and natural world through observation and experiment." Using this definition as a point of departure, she concludes that reliability can indeed qualify as a science because "(1) it shares elements of intellectual and practical activity through the development of methodologies to characterize observed patterns, (2) it considers both the structure and behavior of the systems that it seeks to characterize, and (3) it involves notions of obtaining data (observation) and prioritizes the collection of high-quality data with known pedigree through experimentation" [1]. She remarks that reliability has "elements that expand beyond just a science and contain elements of engineering".

The Oxford English Dictionary definition also builds on a natural science perspective, where the aim is to gain knowledge about the world through observation and experiment. The different conclusions stem from using different criteria for how to interpret the natural science perspective. For example, Singpurwalla refers to the criterion of reproducibility: "A rigorous science is able to reproduce the same result over and over again". However, a pillar of reliability theory is subjective probabilities for which repeated analysis can produce different results even if the data basis is the same. If a reliability scholar writes a scientific paper on the efficient use of subjective probabilities in reliability analysis and publishes it in a reliability journal, does the person then not add anything to the 'reliability science'? Every year a number of papers are published in high-quality reliability journals, enhancing our knowledge about reliability theory and its practice. Every paper makes a contribution to reliability, and is this process not what science is all about?

The philosophy of science literature and fundamental work by Hansson [18] provide support for such a perspective; see also Hansson and Aven [19]. A science can be interpreted as the practice that provides as with the most reliable (i.e. most epistemically warranted) statements that can be produced at the time being on the subject matter covered by the field. It can be argued that reliability is a field or a discipline and, hence, reliability is a science according to this line of thinking.

The main aim of the present paper is to add new insights to the topic of reliability being a science, by pointing to the above ideas and structures for understanding reliability science, presenting its basic pillars and relating it to other fields/sciences such as statistics. Statistics, including probability theory, is a key instrument and field/science supporting reliability. The link to statistics and other fields/sciences is addressed in Section 3, following a presentation of the reliability science

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as defined above in Section 2. In addition to the basic work on science referred to above, key sources for the proposed reliability science definition are Aven [5, 6], as well as documents made by the Society for Risk Analysis (SRA) [37, 38]. In Section 4, some related issues are discussed, for example the importance of acknowledging reliability as a distinct science.

2. The reliability science. basic ideas

The reliability field (discipline) is defined as the totality of educational programmes, journals, papers, researchers, research groups and societies addressing reliability (theory and/or practice). From this understanding of the reliability field, reliability science is defined as the practice that provides us with the most reliable statements (most epistemically warranted statements or most justified beliefs) – i.e. the most updated and justified knowledge - that can be produced at the time being on the subject matter (scope) covered by the reliability field. The scope of this field and science is defined as concepts, principles, approaches, methods and models for understanding, assessing, characterizing, communicating and managing reliability, with applications. Here reliability refers to a system's ability to function as intended. A reliability science book would cover key subjects of this knowledge. The discussion about reliability being a science or not relates to both the practice of generating reliability knowledge and the knowledge itself. The types of research methods used is an example of an issue of the former category (see Sections 4.1 and 4.2), whereas terminology is an example of the latter (see Section 4.4).

The field and science includes in particular activities to assess and understand system reliability, by studying how the system works and can fail, how performance (also capturing failures and failure proneness) changes over time, how the system performance is affected by stress, shocks, etc., how the system performance is affected by maintenance, testing, etc., and how early signs of failure conditions can be identified, as well as using this assessment and understanding to obtain the 'right' reliability for the system, by better designs, more effective maintenance policies, etc., taking into account other relevant aspects like risk and costs [4, 39, 40, 45]. As for all fields and sciences, there are topics at the borderline – what is the subject matter will be subject to continuous discussion. An important issue in this regard is the nexus between different fields and sciences, for example between reliability and statistics, which will be examined in detail in Section 3.

We distinguish between generic reliability (B) and applied reliability (A). Generic reliability covers generic concepts, principles, theories, approaches, methods and models for understanding, assessing, characterizing, communicating and managing reliability. Research aiming to improve the way we should treat uncertainties in reliability studies is an example of generic reliability knowledge generation. If we review reliability journals, we observe that many scientific papers belong to this category of contributions.

Applied reliability covers reliability knowledge generation and communication in relation to specific systems, as well as the tackling of specific reliability problems or issues. For example, to gain knowledge about the reliability of a nuclear power plant, a reliability analysis is conducted, which is applied reliability.

A reliability analysis of a specific system does not necessarily add anything to the reliability science. It may produce new knowledge about the system and, as such, be useful for the practical context and add scientific knowledge to, for example, engineering or medicine, depending on the type of system represented, but the work does not give new insights on the concepts, principles, approaches, methods and models for understanding, assessing, characterizing, communicating and managing reliability. The work is not published in a reliability journal. The work should, however, be supported by reliability science, a science that strives for improvements, benefiting the applications.

There is and should be strong interaction between A and B activities. Developments in B could influence practices in A, and experiences from A activities can lead to new research and developments in B.

A specific reliability analysis could be multidisciplinary and/or interdisciplinary, using competencies from various fields, including reliability. The reliability science provides input to the analysis and the work may also lead to scientific knowledge on reliability. Many cases are presented in reliability journals, showing how the practical work has contributed to new insights on concepts, principles, frameworks, approaches, methods and models.

3. More about the link to other sciences

Analogous to the reliability science, we can define statistical science as the practice that provides us with the most epistemically warranted or justified statements or beliefs that can be produced at the time being on the subject matter (scope) covered by the statistical field, which is essentially about collecting, analysing, presenting, and interpreting data [5, 6]. As for reliability, we can distinguish between applied and generic statistics. Applied statistics (A1) covers statistical analysis of a specific activity to support knowledge generation, communication and management decisions, whereas generic statistics (B2) covers generic concepts, principles, theories, frameworks, approaches, methods and models for collecting, analysing, presenting, and interpreting data.

Reliability science uses statistics but covers many topics not addressed in statistics. For example, work showing that the reliability concept and the reliability science can be viewed as a special case of the risk concept and risk science, respectively (see below), is not in any way covered by the statistical field. Nor are theories and models for reflecting human and organizational factors in the study of system reliability about statistics. Such theories and models would not be presented in a textbook in statistics, as students aiming to learn statistics would not gain any relevant knowledge from these theories and models. These are just examples but illustrate an important point. Statistics does not include the reliability science. Conversely, there is statistical knowledge that extends beyond reliability science, for example knowledge related to general methods for generating statistical estimators and evaluating their properties. See Venn-diagram illustration in Fig. 1. There is an intersection area between reliability science knowledge and statistical knowledge, but there is also knowledge that is not overlapping as discussed above. Statistical knowledge is used in reliability science, but this cannot meaningfully be labelled reliability science knowledge before it is shown that it is in fact relevant to this field. Consider basic research in statistics about deriving improved estimators for settings with rather limited data available. The research is fundamental and is not driven by a desire to improve reliability theory and practice as such, but it could turn out to be highly relevant to this field. The research is in statistics but when applied to reliability, it is also reliability research and science.

Similar types of argumentation can be used for many other fields and

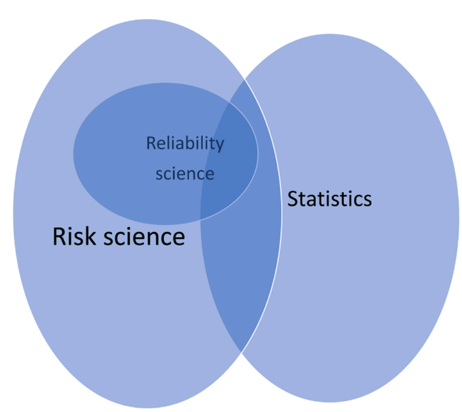

Fig. 1. A Venn-diagram illustration of the relationship between risk science, reliability science and statistics, based on the definitions made of these concepts in this paper.

sciences. Take, for example, mathematics and probability theory. We can consider probability theory as a part of mathematics but also of statistics. Following the overall ideas about what a science is, mathematics can also be viewed as a distinct science, as the practice that provides us with the most epistemically warranted or justified statements or beliefs that can be produced at the time being on the subject matter covered by the mathematical field. Reliability science makes use of both mathematics and statistics.

Clearly, a number of sciences support reliability analysis and management. To structure these, the classification system introduced by Hansson [18] will be used. According to this system, there are five main categories of sciences:

i) nature (natural science),
ii) ourselves (psychology and medicine),
iii) our societies (social sciences),
iv) our own physical constructions (technology, engineering),
v) our own mental constructions (linguistics, mathematics, philosophy).

At first glance, it may seem that reliability should be linked to physical constructions, but further reflection makes it clear that technology/engineering is just one type of applications of reliability science. Basic reliability theory is also used in other areas, in fact in all three areas i) – iii). The system studied need not be a physical construction. It could equally well represent a human being or a community. In addition, applied reliability uses generic reliability, which is to a large extent founded on v). If you consider basic textbooks in reliability, for example Barlow and Proschan [12], the material is about our mental constructions. Concepts, principles, theories, methods and models are introduced and studied, to be able to understand, assess, describe, communicate and manage reliability. Generic reliability uses different types of applications, mainly from technology and engineering, to illustrate the generic knowledge of type v) developed, but it is not dependent on one particular application to be justified.

Risk science has been thoroughly discussed in recent years (e.g. [5, 6, 19]). What has been said above for reliability science also applies to risk science. Risk science is defined as the practice that provides us with the most epistemically warranted or justified statements or beliefs that can be produced at the time being on the subject matter covered by the risk field. The scope of this field is discussed by Aven and Zio [11] and Hansson and Aven [19]. Similar to reliability, it covers concepts, principles, approaches, methods and models for understanding, assessing, characterizing, communicating and managing risk, and a distinction can be made between applied risk (assessment, communication and management) and generic risk (assessment, communication and management).

How reliability relates to risk depends on how risk is defined. There exist many different definitions (see e.g. [2]), but by separating the concept of risk and how it is measured or described, risk science today points to definitions of the risk concept where uncertainty is highlighted as a fundamental component of risk (e.g. [2, 6, 36]). Following the recommendations by the Society for Risk Analysis Glossary [36], the risk concept in its most general form captures basically two main features: a) consequences (C) with respect to something of human value and b) associated uncertainties (U) (what will the consequences be?). We write risk = (C,U). The setting is this [36]: We consider a future activity, for example the operation of a system, and consider the consequences of this activity with respect to something that humans value (e.g. human life and health, environment, economic assets). The consequences are commonly seen in relation to some reference values (planned values, objectives, etc.), and the focus is normally on negative, undesirable consequences. There is always at least one outcome that is considered undesirable or negative.

If risk is understood in this way, the (un)reliability concept can be viewed as an aspect of risk, and hence it can be argued that the reliability field and reliability science are part of the risk field and risk science, respectively (see Fig. 1). The argumentation is as follows.

In relation to reliability science, the context is limited to activities generated by the operation of a system, and the consequences are restricted to failures or reduced performance relative to the system functions. Within this setting, system unreliability can be interpreted as risk [4] – the consequences of the activity are expressed by the system performance, for example through system failure, production loss, etc. Hence (un)reliability = (C,U), with these interpretations of the activity and C. Note that the definition of risk covers both negative and positive consequences; hence, it is a matter of taste whether we refer to risk in this setting as unreliability or reliability. However, to be in line with everyday language, unreliability is preferred.

Risk science provides general knowledge on how to describe risk, and this is consequently also applicable for reliability. In its most general form, risk is described by a specification C' of the consequences C and using a measure (in a wide sense of the word) of uncertainty Q and adding the knowledge K that C' and Q are based on [6, 36]. For the reliability context, C' needs then to be associated with system failures or reduced performance levels, which could be described in different ways, for example using quantities, such as the production loss relative to a planned or maximum level, or simply as an indicator, reflecting whether the system has failed or not. The measure Q would typically be based on probability or probability intervals but should, as argued for in Aven [4], also include judgement of the strength of the knowledge supporting the probabilities. The assessments are often limited to inherent system failures, but external threats to the system function are also relevant, as normally addressed in risk assessments. In addition, the potential for surprises (black swans) should be addressed [4].

Thus, the reliability science can be viewed as a special case of risk science. Commonly, reliability studies provide important input to the risk assessment, for example assessments of the reliability of safety-critical systems and barriers.

Adopting this way of understanding risk, also safety science is covered by the risk science [3]. Safety can be considered the antonym of risk - high risk means low safety and vice versa [3, 36]. From a conceptual point of view, safety science can also be viewed as covering reliability science, as reliability is an aspect of safety, but the focus areas of the respective fields and sciences are very different. Whereas safety science is to large extend founded on the social sciences, highlighting complex and sociotechnical systems, reliability science has its main basis in statistics and engineering. However, reliability science also builds on social sciences. For example, organizational theory and management science constitute important input to reliability management.

4. Discussion

This section discusses some issues linked to the establishment of a distinct reliability science, following up key aspects highlighted by the discussants of the MMR2017 conference. First, in Section 4.1, we look more closely into the science concept and particularly the arguments used to reject a method-based understanding of science. A main point is that science is not the same as a scientific method. Then, in Section 4.2, we discuss the concept of scientific knowledge, defined by the most justified statements and beliefs of the field: how are these statements and beliefs established? In Section 4.3, we discuss why it is important that reliability is broadly recognized as a distinct science. Finally, in Section 4.4, we look into some of the specific challenges addressed at the MMR2017.

4.1. The distinction between the reliability science and the scientific method used for obtaining reliability knowledge

To obtain knowledge about the reliability of a type of unit or system, we perform testing and analysis. The reliability may, for example, be represented by a probability model; by observing failure times, we are able to accurately estimate the distribution. Most textbooks on reliability show how to conduct such analyses. We are applying the 'scientific method' (also referred to as the 'hypothetico-deductive method'). It typically has the following four steps [42]: 1) observations and descriptions of a phenomenon, 2) formulation of a hypothesis to explain the phenomenon, for example using a mathematical relationship, 3) use of the hypothesis to predict the existence of other phenomena or to predict the results of new observations, and 4) performance of experimental tests to verify or falsify the hypothesis. For the reliability setting studied here, the hypothesis in 2) is formulated using a probability model, and, in 3), based on the observations, this model is used to make predictions of the reliability of a new unit or system. If the data show that the model is inaccurate, model changes are needed, and the analysis process repeats. The common framework for carrying out this method is statistical inference. When Singpurwalla ([34], p. 261) refers to scientific criteria related to reproducibility and predictability, he has the scientific method in mind. Statistical analysis is used to describe variability and uncertainties.

The scientific method is a cornerstone in the natural sciences, whose scope covers the study of the physical world and its phenomena, such as physics and biology. It is essential to make a clear distinction between the science per se and the scientific method applied to obtain knowledge within that science. Other methods also exist to gain knowledge and scientific knowledge. 'Conceptual research' is an example and plays an important role in reliability science. Two historical examples of such research include the development of suitable importance measures to identify the most critical components of a system (e.g. [14] and the references therein) and the extension of binary reliability theory to multistate reliability theory (see e.g. [28] and the references therein). A substantial volume of research is conducted to develop the theories, as demonstrated by the many scientific papers published on these topics. 'The scientific method' is not relevant. The conceptual research is about developing suitable concepts and theories, principles, approaches, methods and models, based on reasoning and argumentation. For the multistate example mentioned above, the challenge was to generalize the binary reliability theory to systems allowing more than two states. How should this be done? Alternative ideas were presented and formalized through the introduction of new concepts, theories, principles, methods and models. Their strengths and weaknesses were discussed.

The research typically covers one or more of the following elements: identification (for example, clarifying which binary concepts and principles are also applicable in the multistate case), revision (modifying a binary definition to allow for multistate representation of the system), delineation (for example, focusing on monotone systems only), summarization (to see the wood for the trees, for example allowing for only a finite set of states), differentiation (for example, differentiating between different categories of multistate systems – such as coherent and monotone systems), by advocating (for example, argumentation to justify or support a set of assumptions for defining a multistate system), and refuting (for example, argumentation aimed at rebutting a given perspective) [6, 24]. The quality of conceptual research is evaluated in the same way as other types of research: by references to criteria such as *exposition* (conceptual clarity and internal consistency), *theory building* (e.g. precision and rationale), *innovativeness, potential impact* and *validity* (reflecting the degree to which one is able to conceptualize what one would like to conceptualize) [6, 43]. It is also common to refer to the following four criteria: originality, solidness, relevancy and usefulness (see e.g. [9]). Scientific work is also characterized by a set of general norms and standards, such as the four institutional imperatives: Universalism, Communality, Disinterestedness, and Organized Skepticism [19, 27].

Research meeting these criteria and published in well-recognized scientific journals is today broadly acknowledged as scientific. This research is an activity of the reliability field and discipline, which covers all relevant educational programmes, journals, papers, researchers, research groups and societies, etc., as mentioned in Section 2.

The methods for deriving scientific knowledge are continuously developing. This is a feature that characterizes science. A major strength of science is its capability of self-improvement [19]. A method-based delimitation of science can only have temporary validity, as discussed by Hansson [18]. A famous example of a 'method-founded science' is Karl Popper's falsifiability criterion, according to which "Statements or systems of statements, in order to be ranked as scientific, must be capable of conflicting with possible, or conceivable observations" ([29], p. 39). This criterion, as all such criteria, has severe problems, as thoroughly discussed in the literature. Most of them are suitable only for some, not all, of the science disciplines, and all of them make the science of previous centuries unscientific, although it was the best of its day.

Singpurwalla ([34], p. 261) applies a type of method-based delimitation of science when referring to a set of characteristics of the method of natural sciences, covering 'clarity on concepts', quantifiability, controllability, reproducibility and predictability. He argues that reliability fails to meet these criteria and is therefore not a science. For the framework presented in Section 2, to meet all of these criteria we have to restrict attention to applied reliability for situations where repeated, controlled experiments can be conducted to gain knowledge about the systems studied. However, the scope of applied reliability and reliability in general extend far beyond situations characterized by such experiments, and for the reliability field to be sufficiently broad and develop further, it is considered essential to not separate the generic reliability and the applied reliability. The core of the reliability field is the generic part. See also discussion in Section 4.3.

4.2. Determining the most justified statements and beliefs of the reliability field

In Section 2, reliability science was defined as the practice that provides us with the most epistemically warranted or justified statements or beliefs that can be produced at the time being on the subject matter (scope) covered by the reliability field. A number of papers have been produced on reliability, but what are the most justified concepts, theories, principles, approaches, methods and models of the field?

In some cases, the answer is clear; in others it is not. Which are the best are contested. Science is characterized by a continuous 'battle' on what these statements and beliefs are – it is about institutions and power. Different schools of thought argue for their beliefs, trying to influence and control the field [15]. It is the same for reliability science. For example, for years we experienced an intense discussion about the suitability of the Bayesian perspective (see e.g. [13, 16, 22]). Argumentation was provided for why this perspective was unscientific, the main problem being the use of subjective probabilities. However, the Bayesian advocators rejected this view. Instead, they highlighted the need to use all relevant information and knowledge to adequately support the decision-making. A different perspective on science was required.

For any field and science to develop, it is essential that there is continuous questioning and scrutiny of the current concepts, theories, principles, approaches, methods and models. Critique is a cornerstone of the scientific system. However, at the same time, any field and science needs to clarify what is its core knowledge at any point in time. This amounts to concepts, theories, principles, approaches, methods and models. If we look at reliability textbooks today, it is not difficult to identify a number of topics for which there is broad consensus about belonging to the core subjects of the reliability field and science. Both the traditional statistical approach and the Bayesian approach are used to analyze reliability. Through integrative thinking, the scientific 'battle' about Bayesian ideas and methods has led to new insights and a broader set of instruments for understanding and analysing reliability. An integrative process is a form of thinking which reflects a strong "ability to face constructively the tension of opposing ideas and instead of choosing one at the expense of the other, generate a creative resolution of the tension in the form of a new idea that contains elements of the opposing ideas but is superior to each" ([25], p. 15). In this particular case, there were different perspectives on how to approach and analyze data, which can be considered to create tension. However, integrative thinking makes the analysts see beyond these perspectives – it utilizes the opposing ideas to obtain a new and higher level of understanding.

Despite broad agreement on many areas, it is not difficult to point to issues where there are discussions on what are the most warranted statements and justified beliefs concerning concepts, principles, approaches, methods and models. An example is how to express uncertainties in relation to reliability characterizations. For many scholars, probability is the answer, whereas others argue for the need to use alternative approaches, such as possibility theory and evidence theory. Different 'schools' have been developed with rather limited interactions and communication. However, as for most situations, when this type of disconnection occurs, it is important to seek arenas for dialog where relevant views and assumptions made are discussed. The result is often new knowledge and improved concepts, approaches, methods and models. An example is the work reported in Aven et al. [7], in which, over a five-year period, the authors studied different perspectives on how to best treat uncertainties in a risk and reliability context. The work did not result in full consensus on what is the preferred approach in all types of situations, but it clarified what the different perspectives mean, their strengths and weaknesses, and how they are to be used in practice. Then it is up to the analyst to choose an approach in a specific case, considering the arguments provided for the alternatives available. Our studies on this topic have shown that many risk and reliability researchers are not familiar with the concept of subjective (knowledge--based, judgemental) probability to describe uncertainties. They apply an alternative non-probabilistic approach, by arguing that, because of uncertainties, probability cannot be quantified. However, a subjective probability can always be quantified. The problem is that the knowledge supporting it can be more or less strong. Addressing this knowledge and its strength, and allowing for imprecise probabilities in addition to precise probabilities, a practical framework for uncertainty descriptions can be made [4]. Similarly, arguments can be provided for alternative perspectives. The risk and reliability sciences develop this type of knowledge, building a knowledge base of the most justified beliefs of the field.

It is underlined that this section does not aim at providing an overview of current issues being debated or contested within reliability science. Rather the section seeks to give substance to the concept of 'most justified knowledge', by providing some general reflections as well as presenting some illustrating examples.

4.3. Recognition of reliability (risk) as a distinct science

The reliability field today is not broadly recognized as a distinct science. The discussion about the topic at MMR2017 [1, 32, 34, 44] shows that, among reliability scholars, there are different views on the importance of reliability being considered a science. Some even argue against the idea that reliability is a science. The present paper has provided a framework in which reliability is in fact a distinct science or, alternatively, is seen as a part of a distinct science (risk science). Many arguments can be used to support such a distinct science perspective. They are very similar to those that apply to, for example, statistics and risk.

Fighting for turf, for authority and status for risk (reliability) science, is a fight for substance: enhanced risk (reliability) analysis and management to the benefit of all types of applications and in this way a strengthening of the risk (reliability)-informed decision-making [8]. As discussed in Aven [[6], Preface], the total volume of research, as well as the number of academic study programmes and positions in generic risk and reliability analysis, is rather small, if we compare it with, for example, statistics. Today, there are not many specific risk or reliability science professors worldwide. The current positions and educational programmes are typically linked to specific applications, particularly different domains of engineering. However, most of the concepts, principles, methods and models are general and relevant to a variety of applications. It is essential for the development of the field that there is a generic knowledge base, where input is gained from different applications and guidance is produced for new situations and problems. If the science is restricted to each domain of application, little progress will result, as there will be limited ways of learning and building on insights from different types of problems. Instead, statistics, risk and reliability science should extend beyond the specific applications, through their generic knowledge generation on concepts, principles, frameworks, approaches, methods and models.

How the different fields are organized is also about what is practical. If the scope of the science is too wide, people would find too much work irrelevant and develop subcommunities, which in turn could lead to separation and the creation of new fields and sciences. On the other hand, if the scope is too narrow, the input and discussions could be too limited, with the result that the field does not show sufficient development and progress. A distinct science needs to have a sufficiently large volume, when it comes to students and researchers. There will always be changes in the job market; an application area can be popular at some point in time but for different reasons its appeal can be reduced or lost. A more generically based science is, however, more robust in the sense that it is relevant to a number of applications, and, depending on the current hot topics, it can easily be oriented towards these applications. By seeing reliability in connection with statistics and risk, the robustness is further strengthened, and, as argued for in this paper, the three areas form a natural basis for study programmes and research.

In practice, such an integration could, however, be difficult in many cases. As commented by one of the reviewers of the present paper, we see today a flourishing of biostatistics departments all over the world, while statistics is on its way to merge with data science and computer science. In such situations it will clearly be difficult to integrate the statistical environments and those focusing on reliability and risk. The result is often that risk is highlighted, with reliability as an important subtopic, but we also find other arrangements, for example focus on reliability and quality management.

4.4. Some challenges raised

The reliability science faces many challenges. The purpose of the present paper is not to present an overview of these but to discuss basic issues related to reliability science: its foundation and link to risk science and other sciences. The paper uses examples to illustrate this discussion, to large extent following up the MMR2017 conference and in particular Singpurwalla et al. [34].

Singpurwalla addresses the terminology challenge [34]. He states that for "reliability to be labelled a science, it should necessarily satisfy the requirement of an unambiguous and clearly accepted terminology". According to Singpurwalla, that is not the case today. His-main argument is that "to many, practically every reader of this article, reliability is a probability, and probability is not uniquely defined nor can it be directly measured". He refers to different interpretations, including the propensity and chance concept and subjective probability.

As a response to this, it should be stated that probability as a concept is used with different interpretations, and these are well-known and established today, although there has been an intense debate historically about the issue and many scholars and practitioners still struggle with being precise on this matter. For reliability science, we can precisely define classical probabilities, frequentist probabilities (propensities, chances) and subjective (judgemental, knowledge-based) probabilities; see for example Singpurwalla [33], Lindley [23] and Aven and Reniers [10]. The current clarification can be viewed as a result of developments within the risk and reliability field and science. For the existence of reliability science, it is not a problem that different interpretations of the concept probability exist, as long as clear definitions and interpretation can be provided.

A key problem in this regard is the lack of clarity on the interpretation of subjective probabilities. Lindley [23] has provided a theoretical rational and strong argumentation for a way of interpreting such a probability, but reference is still often made to some of the earlier understandings, which are based on a mixture of uncertainty assessments and value judgements (how the assessor likes money); see discussion in Aven and Reniers [10].

Today, clarity exists on the link between precise and imprecise probability, and the need to support subjective probabilities (exact or imprecise) by judgements of the strength of the knowledge supporting these probabilities, as mentioned in Section 4.2. How to do this is a research challenge for the risk and reliability fields and sciences. The use of imprecise probability makes the transformation from knowledge to probability less subjective, but it does not make the knowledge as such more objective.

Singpurwalla concludes that reliability is an essential technology – like statistics; it is not a basic or a natural science. Following Singpurwalla, what characterizes reliability is that it leans on the "the application of science, the philosophy of science, the language of science, and the technology of science to facilitate decision making in the face of uncertainty". According to Singpurwalla, mathematics, statistics and engineering are not sciences: "However, reliability also fails the other attributes of the hard sciences because the subject of reliability entails a craftful combination of engineering (not a science), mathematics (the language of science), and statistics (the technology of science)."

If the criterion for being a science is that it meets the criteria of natural science, there would be no discussion about this conclusion. Reliability is not a natural science, as pointed out in Sections 3 and 4.1. By also rejecting fields such as mathematics and statistics as sciences, the logical implication is the one made by Singpurwalla. There are, however, good reasons to recognize other sciences, such as mathematics and statistics, as distinct sciences, as thoroughly discussed in the philosophy of science literature (e.g. [18]) and to some degree also in the present paper. Clearly, if statistics is justified as a science, reliability can be. As mentioned in Section 1, several of the discussants of MMR2017 pointed to the dependencies of the conclusions on how science is defined.

The MMR2107 discussion also addresses challenges – and opportunities - related to the use of 'big data', driven by developments in information and communication technology (ICT), including sensor and storage technology, coupled with advancements in artificial intelligence and statistics, including data mining, machine learning and statistical learning theory (e.g. [8, 20, 41]). Vitali Volovoi ([34], pp 262–266) points to the importance of reliability to integrate data-driven models based on correlation, with cause analysis. Lawless [21] argues along the same lines, stressing that statistics and reliability theory are indispensable if we wish to truly understand systems. See also discussion in Meeker and Hong [26], Göb [17] and Sharma et al. [35].

5. Conclusions

Based on the discussion at MMR2017 regarding whether reliability is a science, the present paper has argued for the thesis that reliability is a distinct science, alone or integrated with risk, and that it is important for it to be broadly acknowledged as such. This science's main pillars are described and discussed. For the reliability field to further develop, it is essential that the community of reliability- and risk scholars backs work on strengthening the scientific basis of the field. We need strong research groups and champions that can take reliability to the next stage as a science. To this end, it is necessary to see beyond the strict reliability field. A more robust scope needs to be developed, covering risk analysis and management, but other topics should also be considered, such as safety science. Uncertainty analysis is closely related to risk, but in many respects there is a separation between the risk and uncertainty environments. To successfully develop a distinct reliability, safety and risk science, leaders from the different environments should join forces. The issue should be focused on at conferences covering all these topics.

Author statement

The work has been carried out fully by Terje Aven

Declaration of Competing Interest

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

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References

[1] Anderson-Cook CM. Discussion of "Is reliability a new science?". Appl Stoch Models Bus Ind 2019;35:270–1. https://doi.org/10.1002/asmb.2423.
[2] Aven T. The risk concept. Historical and recent development trends. Reliability Eng Syst Safety 2012;115:136–45.
[3] Aven T. What is safety science? Saf Sci 2014;67:15–20.
[4] Aven T. Improving the foundation and practice of reliability engineering. Proceedings of the Institution of Mech Eng, Part O: Journal of Risk and Reliability 2017;231(3):295–305. Open access.
[5] Aven T. An emerging new risk analysis science: foundations and implications. Risk Anal 2018;38(5):876–88. Open access.
[6] Aven T. The science of risk analysis. New York: Routledge; 2020.
[7] Aven T, Baraldi P, Flage R, Zio E. Uncertainty in risk assessment. Chichester: Wiley; 2014.
[8] Aven T, Flage R. Foundational challenges for advancing the field and discipline of risk analysis. Risk anal 2020;40(S1):2128–36.
[9] Aven T, Heide B. Reliability and validity of risk analysis. Reliability Eng Sys Safety 2009;94:1862–8.
[10] Aven T, Reniers G. How to define and interpret a probability in a risk and safety setting. Discussion paper, with general introduction by Associate Editor. Genserik Reniers. Safety Sci 2013;51:223–31.
[11] Aven T, Zio E. Foundational issues in risk analysis. Risk Anal 2014;34(7):1164–72.
[12] Barlow R, Proschan F. Statistical theory of reliability and life testing. New York: Holt, Rinehart and Winston; 1975.
[13] Bernardo J, Smith A. Bayesian theory. Chichester: John Wiley; 1994.
[14] Borgonovo E, Aliee H, Glaß M, Teich J. A new time-independent reliability importance measure. Eur J Oper Res 2016;254(2):427–42.
[15] Bourdieu P, Wacquant LJD. An invitation to reflexive sociology. Chicago: University of Chicago Press; 1992.
[16] Easterling RG. A personal view of the Bayesian controversy in reliability and statistics. IEEE Trans Reliab 1972;R-21(3):186–94.
[17] Göb R. Discussion of Reliability meets big data: opportunities and challenges. Qual Eng 2014;26:121–6.
[18] Hansson SO. Defining pseudoscience and science. In: Pigliucci M, Boudry M, editors. Philosophy of pseudoscience. Chicago: University of Chicago Press; 2013. p. 61–77.
[19] Hansson SO, Aven T. Is risk analysis scientific? Risk Anal 2014;34(7):1173–83.
[20] Hastie T, Tibshirani R, Friedman J. The elements of statistical learning – data mining, inference and prediction. 2nd ed. New York: Springer; 2017.
[21] Lawless JF. Contribution to panel discussion. Appl Stochastic Models Bus Ind 2019; 35:272–3.
[22] Lindley DV. The philosophy of statistics. The Statistician 2000;49:293–337. With discussions.
[23] Lindley DV. Understanding uncertainty. Hoboken, NJ: Wiley; 2006.
[24] MacInnis DJ. A framework for conceptual contributions in marketing. J Mark 2011;75(4):136–54.
[25] Martin R. The opposable mind. Boston: Harvard Business Press; 2009.
[26] Meeker WQ, Hong Y. Reliability meets big data: opportunities and challenges. Qual Eng 2014;26(1):102–16. With Rejoinder: pp 127-129.
[27] Merton RK. Science and technology in a democratic order. J Legal and Political Sociol 1973;(1):115–26. 1942. Reprinted as The normative structure of science. In R.K. Merton The Sociology of Science. Theoretical and Empirical Investigations. Chicago: University of Chicago Press; 1973 267-278.
[28] Natvig B. Multistate systems reliability theory with applications. Chichester: John Wiley; 2011.
[29] Popper K. Conjectures and refutations. the growth of scientific knowledge. New York: Basic Books; 1962.
[30] Rocchi P. Can the reliability theory become a science? Reliability: Theory and Application 2015;10(36):84–90.
[31] Rocchi P. Reliability is a new science: gnedenko was right. Cham, Switzerland: Springer International Publishing AG; 2017.

[32] Rykov V. Reliability is a new science: gnedenko was right. Appl Stoch Models Bus Ind 2019. 1-1.
[33] Singpurwalla ND. Reliability and risk: a bayesian perspective. New York: Wiley; 2006.
[34] Singpurwalla ND, Volovoi V, Brown M, Peköz EA, Ross SM, Meeker WQ. Is reliability a new science?. In: A paper from the panel session held at the 10th International Conference on Mathematical Methods in Reliability. Applied Stochastic Models in Bus and Industry. 35; 2019. p. 260–9. https://doi.org/10.1002/asmb.2442.
[35] Sharma S, Kumar N, K. Kuldeep Singh. Big data reliability: a review. J. Intel Fuzzy Sys 2021;40(3):5501–16.
[36] SRA. Glossary society for risk analysis. 2015. www.sra.org/resources. Accessed January 7, 2020.
[37] SRA. Core subjects of risk analysis. a. 2017. www.sra.org/resources. Accessed January 7, 2020.
[38] SRA. Risk analysis: fundamental principles. b. 2017. www.sra.org/resources. Accessed January 7, 2020.
[39] Thompson WA. On the foundations of reliability. Technometrics 1981;23(1):1–13.
[40] Ushakov I. Reliability theory: history and current state in bibliographies. Reliability: Theory & Applications 2012;1(24):8–35.
[41] Vapnik V. The nature of statistical learning theory. New York: Springer; 2013.
[42] Wolf F. Essentials of scientific method. New York: Routledge; 2018.
[43] Yadav M. The decline of conceptual articles and implications for knowledge development. J Mark 2010;74(January):1.
[44] Zhang J, Zhang Q, Kang R. Reliability is a science: a philosophical analysis of its validity. Appl Stoch Models Bus Ind 2019;35:275–7. https://doi.org/10.1002/asmb.2426.
[45] Zio E. Reliability engineering: old problems and new challenges. Reliability Eng Sys Safety 2009;94:125–41.