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A risk and safety science perspective on the precautionary principle

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ABSTRACT

The precautionary principle is strongly debated as a policy for handling risk and safety concerns. It is commonly claimed that the principle is paralyzing, unscientific and promotes a culture of irrational fear. The risk and safety literature contains considerable work providing support for such claims but also argumentation backing the principle. The present paper aims at contributing to this discussion by investigating the principle in view of what is here referred to as contemporary risk and safety science. Common beliefs about the principle are revisited. New insights are obtained by clarifying the risk and safety fundamentals necessary to understand the principle's motivation, applicability and limitations. The paper concludes that the precautionary principle is only relevant when the uncertainties and risks are considerable and scientific. Confusion arises, as the principle is mixed with the basic idea of risk management to give weight to uncertainties, in order to prudently handle risk. Properly understood and implemented, the precautionary principle can be aligned with decision analysis and other scientific methods.

1. Introduction

This paper discusses the understanding, rationale and use of the precautionary principle, which is a basic risk and safety science[1] principle frequently referred to and applied when decisions are made under risk and uncertainty. The principle is a cornerstone of European Union (EU) regulations and law (EU, 2002,2017,2022): It has a general form, expressing a normative obligation or position, which is applied in specific contexts. It is common also to express that the basic idea of the principle is reflected by the saying "an ounce of prevention is worth a pound of cure" or "better safe than sorry" (Rechnitzer, 2020, Miller and Engemann, 2019).

Despite considerable use, the precautionary principle is highly controversial. It is commonly argued that the principle is paralyzing, unscientific and promotes a culture of irrational fear. Rechnitzer (2020), see also Randall (2009) and Miller and Engemann (2019), summarizes some aspects of this criticism, as well as arguments commonly used to support the principle. A main point made in Rechnitzer's discussion is that there is a range of interpretations of the principle, and it therefore makes sense to speak about precautionary principles in the plural.

The present paper is based on the conviction that the controversies to large extent are rooted in a lack of clarity of the meaning and scope of the principle. Adopting an interpretation of the principle in line with the sayings referred to above, strong arguments can be provided for why the principle is unscientific in many cases. However, if other interpretations of the principle are used - restricting the invocation to cases characterized by fundamental uncertainties - this type of reasoning would fail – as the principle then is applied when science do not provide clear answers.

The present paper aims at clarifying the meaning, justification and scope of the principle, by conducting analysis of this type, distinguishing between different interpretations of the principle. Following Sandin et al (2002) and Rechnitzer (2020), three types of features or characteristics of the principle are highlighted: threat, uncertainties and actions/commands. New insights are gained by adopting what the present author considers to be a contemporary risk science perspective. This perspective is built on recent documents produced by the Society for Risk Analysis (SRA, 2015, 2017) and related supporting literature (see e.g. Aven, 2016; Logan et al., 2021; Aven and Thekdi, 2022). The SRA documents have been developed by a broad group of senior risk scientists – with different backgrounds and competencies – and with input from members of the society. A key point in this literature is the clear distinction between concept definitions (which are broad and qualitative) and the related concept measurements or descriptions (which could be quantitative, qualitative or a combination).

This perspective provides input on the understanding and use of the precautionary principle, and in particular the three characteristics: the threat, uncertainties and actions/commands. A key factor is the type and degree of uncertainty. The literature on this is not straightforward, with numerous suggestions on how to classify the situations considered, using different characterizations of the uncertainties and related concepts like knowledge, probabilities and risk. Using the risk science perspective, clarity on key concepts and their interrelationship are obtained, and practical guidance can be provided on when and how to use the principle.

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[1] To simplify the notation, in the following, we refer to risk science and not to risk and safety science.

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The work can be seen as conceptual risk and safety research as explained in Section 2. There are problems concerning the understanding and use of the precautionary principle as explained above. This triggers a need for re-evaluation of current thinking and the development of new ideas and perspectives. The current paper provides such ideas and perspectives, using contemporary risk science knowledge. The result is new knowledge on the interpretation and use of the precautionary principle, which provides improved clarity on the rationale of the precautionary principle as well as some guidance for how to use the principle in practice.

The rationale of the precautionary principle has been discussed from many different perspectives, addressing both theoretical and practical issues. The theoretical discussions have to a large extent been conducted by philosophers, decision analysts and economists, relating the precautionary principle to decision rules, such as the expected utility theory (Bayesian decision analysis) and the minimax method (see overview in Rechnitzer, 2020). The present paper discusses the applicability of the decision rule approach and decision analysis in general when adopting the risk science perspective. Again, the aim is to improve the understanding and clarity of the key concepts in the practical risk context. The practical challenges related to the precautionary principle have been discussed from different perspectives, particularly those of law and regulations (e.g., Sunstein, 2005; Löfstedt, 2014; Hansson, 2020).

Many researchers have made contributions to the understanding and use of the precautionary principle. Some of these have been mentioned above. The aim of the present study has not been to give a comprehensive review of the literature on the precautionary principle. For the purpose of the present study, reference has been made to some selected works which summarize what is considered current ideas and practices concerning the understanding and use of the precautionary principle.

The main scientific contributions of the paper can be summarized as follows (more details are provided in Section 7):

– An enhanced understanding of the rationale of the precautionary principle, on both conceptual and management issues, by using contemporary risk science knowledge
– An enhanced understanding of the relationship between the precautionary principle and decision analysis and decision analysis methods

The paper is organized as follows. First in Section 2 the methodological approach for the research work is described. Then in Section 3 a brief review of current beliefs, ideas and statements about the precautionary principle is given, following up the above introduction. Then, we discuss the meaning, rationale and use of the principle, in view of the risk science perspective referred to. Section 4 addresses conceptual issues, whereas Section 5 management issues. Section 6 presents the recommended approach and discusses in more detail some of the issues raised in the previous sections. Finally, Section 7 concludes. Various aspects of the coronavirus and COVID-19 pandemic are used to illustrate the analysis and discussion in Sections 4–6, in particular issues linked to the societal shutdowns (lockdowns) medio March 2020. The paper argues that Governments gave weight to the precautionary principle when making the lockdown decisions.

2. Methodological approach

This paper can be viewed as conceptual risk and safety research as discussed in Aven (2018), covering concepts, principles, approaches, methods and models for understanding, assessing, communicating and handling risk and safety. Reasoning and argumentation are the key instruments. This type of research work builds on elements such as identification, revision, delineation, summarization, differentiation integration, advocating and refuting (MacInnis, 2011; Aven, 2018). The following examples illustrate these elements for the present study:

- Identification: To identify common definitions of the precautionary principle, to identify key challenges related to current interpretations and use of the precautionary principle
- Revision: To change or adjust interpretations by using contemporary risk science knowledge
- Delineation: To focus the study on fundamental ideas more than practical challenges related to the implementation of the precautionary principle
- Summarization: To state main issues and points concerning the understanding and use of the precautionary principle
- Differentiation: To distinguish between alternative definitions and interpretations
- Integration To build and combine scientific contributions addressing various topics relevant for the understanding and use of the precautionary principle
- Advocating: To argue for the rationality of the precautionary principle
- Refuting: To rebut the idea that the precautionary principle is to be seen as a decision rule and is consistent with the minimax decision strategy, to rebut the idea that there is a conflict between the precautionary principle and decision analysis.

As mentioned in Section 1, the SRA documents and related research work provide the reference when referring to contemporary risk science knowledge. There is a subjective element in deciding what this knowledge includes; this is acknowledged, but a reference is needed to clarify the premises for the conclusions made. Building on the comprehensive work by the SRA, the foundation for the analysis is considered rather broad and strong. It is traceable and allows for and will hopefully encourages further scientific discussions.

3. Review of some current beliefs, ideas and statements about the precautionary principle

Many definitions of the precautionary principle exist. Most of them differ with respect to three types of features or characteristics: threat, uncertainties and actions/commands (Sandin et al., 2002; Rechnitzer, 2020), as illustrated for some definitions of the precautionary principle in Table 1. There are many interpretational issues related to these definitions and features, to be reviewed and discussed in the following. At the end of this Section 3, some other issues concerning the precautionary principle are addressed, including decision analysis and the claim about the principle being unscientific.

The examples in Table 1 illustrate the spectrum of different types of definitions suggested and used, pointing to various aspects of risk and risk handling. Historically the first one, the Rio declaration - as a result of the United Nations Conference on Environment and Development (UNCED) in 1992 - is one of the most prominent and influential definitions of the precautionary principle. It has a focus on environmental issues and is built on the concept of scientific certainty (and hence also uncertainty). The second definition in Table 1 (Raffensperger and Tickner, 1999, pp. 353–354), is interesting as it relates the application of the precautionary principle to cause-effect relationship and is explicit on the idea of 'reversed burden of proof'. The third definition (HSE 2001) has been instrumental for the use of the principle in UK. It is interesting from a risk science perspective as it refers to likelihood judgments. The fourth example, from EU, is included as the precautionary principle plays an important role in risk management in Europe, and its formulation is general and covers a statement about regulatory action. The SRA (2015) definition is referred to as it has been approved by Society for Risk Analysis following a recommendation from a risk analysis and risk science expert committee. The final example, "Better safe than sorry", is included as it is common to relate the precautionary principle to this saying.

Table 1
Examples of definitions of the precautionary principle, with characterizations of the three features: threat, uncertainty and action/command.

Features Definitions	Threat	Uncertainty	Action/command
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 (1992 Rio declaration).	Threats of serious or irreversible damage	Lack of full scientific certainty	The uncertainties shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation
When an activity raises threats to the environment or human health, precautionary measures should be taken, even if some cause-and-effect relationships are not fully established scientifically. In this context, the proponent of an activity, rather than the public, should bear the burden of proof of the safety of the activity (Raffensperger and Tickner, 1999, pp. 353–354).	When an activity raises threats to the environment or human health	Some cause-and-effect relationships are not fully established scientifically	Precautionary measures should be taken "Reversed burden of proof"
The precautionary principle should be invoked where: there is good reason, based on empirical evidence or plausible causal hypothesis, to believe that serious harm might occur, even if the likelihood of harm is remote; andthe scientific information gathered at this stage of consequences and likelihood reveals such uncertainty that it is impossible to evaluate the conjectured outcomes with sufficient confidence to move to the next stages of the risk assessment process (HSE, 2001).	Serious harm might occur	The scientific information gathered reveals such uncertainty that it is impossible to evaluate the conjectured outcomes with sufficient confidence	As for the Rio 1992 declaration, as HSE (2001) refers to this definition of the precautionary principle
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, 2017,2022).	Potentially hazardous agents might induce harm to humans or the environment	Conclusive evidence about the potential harmful effects is not (yet) available	Regulatory actions may be taken
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 (SRA, 2015).	The consequences of the activity could be serious	The consequences are subject to scientific uncertainties	Precautionary measures should be taken, or the activity should not be carried out
"Better safe than sorry." (Rechnitzer, 2020) (Possible interpretations: be cautious so that you do not make a decision you will later regret; it is better to choose the safer option than the riskier one, because if you decide to go with the riskier option, then you may later regret it; even if it is uncertain whether an activity will lead to harm, measures should be taken to prevent harm.)	A risk	Any type	Be cautious, choose the safer option, preventive measures should be taken

3.1. The threat

Sandin (1999) interprets 'threat' in this context to mean undesirable possible states of the world, such as global warming, loss of biodiversity, drastically reduced average length of life, and disease. A key characteristic of a threat is its seriousness. In environmental contexts, the concept of irreversible damage is commonly used as an important aspect of the seriousness of the threat. In general, it is common to refer to a threat as an event or risk source with the potential for some undesirable consequences (SRA, 2015).

3.2. Uncertainties

Again referring to Sandin (1999), the uncertainty dimension expresses our (lack of) knowledge of the possible states of the world defined by the threat. Typical phrases are "lack of full scientific certainty", "the consequences are subject to scientific uncertainties" and "before a causal link has been established by absolutely clear scientific evidence". In line with this thinking, the threat dimension concerns ontology, whereas the uncertainty dimension concerns epistemology.

As noted by Sandin (1999), most formulations of the precautionary principle interpret the uncertainty in question as scientific uncertainty. The European Union and the signatories of international treaties on environmental protection apply a similar interpretation, seeing the precautionary principle as a guideline specifying how to deal with scientific uncertainty (Hansson, 2020). The term 'scientific uncertainty' can, however, been interpreted in many ways, as thoroughly discussed in the literature; see for example Sandin (1999), Stirling (1999,2008), Aven (2011), Cox (2011), North (2011) and Vlek (2011). One perspective is to relate the scientific uncertainties to the difficulty of establishing accurate prediction models for the consequences considered (Aven, 2011). Many of the current interpretations of scientific uncertainties build on the Knightian risk-uncertainty framework, for example Stirling and Gee (2003), who relate scientific uncertainties to cases in which we have poor knowledge about the likelihoods, and the outcomes are poorly defined.

The uncertainty dimension relates to the threat and its consequences. Regarding the former aspect, HSE (2001) states that the precautionary principle should be invoked where "there is good reason, based on empirical evidence or plausible causal hypothesis, to believe that serious harm might occur, even if the likelihood of harm is remote". Randall (2011, p. 186) expresses a similar view: "Credible scientific evidence of plausible threat of disproportionate and (mostly but not always) asymmetric harm calls for avoidance and remediation measures beyond those recommended by ordinary risk management" (Randall, 2011, p. 186). When it comes to the latter aspect concerning the uncertainties of the consequences, HSE (2001) formulates a criterion for invoking the precautionary principle, stating that "the scientific information gathered reveals such uncertainty that it is impossible to evaluate the conjectured outcomes with sufficient confidence".

Peterson (2006) argues that the precautionary principle cannot meaningfully be restricted to situations of ignorance, as some scholars have argued for (see e.g. Resnik, 2003, 2004), as, to apply the "principle to any particular problem, one must make judgments regarding the plausibility and seriousness of a threat" (Peterson, 2006). Hence, according to Peterson (2006), some relevant information must be available. He refers to the 1992 Rio Declaration, for which the criterion for invoking the precautionary principle is that there is a lack of *full* scientific certainty (see Table 1).

On the other hand, Peterson (2006) argues that the precautionary principle is not meaningfully used when objective probabilities exist and are known to the decision maker for all outcomes of the alternatives considered, as, in such cases, theories exist, particularly the expected utility theory, which can guide the decision-making.

3.3. Action/command

Sandin (1999) distinguishes between action and commands. The action dimension concerns what response to the threat is specified or prescribed and covers statements like "precautionary measures", "regulatory action" and "cost-effective measures to prevent environmental degradation". The command dimension expresses the status of the action and includes terms like "should be taken", "may be taken". In this present discussion, we see these two dimensions together, reflecting the decision aspect of the precautionary principle.

A main issue of the action/command discussion relates to the degree to which the precautionary principle prescribes what to do: Is the principle a decision rule or just a general statement of a normative position for a class of situations – a perspective for the risk handling (Randall, 2009, 2011; Aven, 2019c)? Following Peterson (2007), a decision rule is to be seen as a logical statement of the type "if [condition], then [decision]". As expressed by Peterson (2007), "A decision rule simply tells decision-makers what to do, given what they believe about a particular problem and what they seek to achieve". Several philosophers and decision analysts have theoretically shown that, if the precautionary principle is to be interpreted as a decision rule, it leads to some rationality problems, including incoherency (e.g. Peterson, 2006; Stefánsson, 2019). According to Peterson (2006,2007), the precautionary principle needs to be interpreted as a decision rule to have a normative content. If interpreted as a normative position or perspective for the risk handling, it is not designed to tell us what to do and what not to do for each possible input of information (Sunstein, 2005; Peterson, 2007).

Relevant to this discussion is the difference between a principle and a rule (e.g. Randall, 2011; Rechnitzer, 2020). A rule prescribes what follows when certain conditions are met, whereas a principle expresses normative obligations that are to be implemented/operationalized according to the context in which it is used (Randall, 2011, p. 97).

As discussed by many authors, principles, even if they are rather general and do not directly recommend a specific decision, could have an impact on the decision-making process (e.g., Randall, 2011; Steel, 2013, 2014; Rechnitzer, 2020). In society, industry, business and life in general, there is a continuous 'battle' between development on the one side and protection on the other (Aven, 2019a). This battle is a result of differences in values and priorities, as well as in knowledge and scientific perspectives. For example, public administration is strongly guided by CBAs (cost-benefit analyses), which means that uncertainty and risk considerations are given rather limited attention beyond expected values. Hence, it can be argued that the development concern, more than protection, is highlighted. Building on CBAs, the nuclear industry in a country would normally be 'justified'. A principle favouring protection has an important role to play in relation to this type of consideration and management: "A warning is in place – there is a potential for serious consequences and there are uncertainties. The development tools have spoken – now it is time for the protection side to highlight important aspects for the decision-makers to adequately balance the various concerns" (Aven, 2019a).

The decision rule interpretation of the precautionary principle is questioned by several authors (Randall, 2011; Aven, 2019c; Rechnitzer, 2020). The key argument used is that, given that the precautionary principle is to be applied in the case of scientific uncertainties, frameworks for prescriptive decision-making cannot be justified. The knowledge is too weak. Probabilities that are assigned would have a weak basis and could not be used as a confident measure of uncertainty. Enumerating all possible outcomes could also be difficult. As Randall (2011, p. 86) explains, the conditions used by Peterson (2006) to show incoherency and rational choice have a place in ordinary risk management frameworks but not in those of scientific uncertainties, see discussion in Boyer-Kassem (2017a,b), Peterson (2017) and Aven (2019c).

3.4. Decision analysis

Decision analysis has discussed operationalizing the precautionary principle in many ways, see review by Rechnitzer (2020)- As an example, consider the minimax decision rule. It expresses that we should select the option with the best worst case in order to 'minimize the maximum'. As discussed in the literature (see Rechnitzer 2020), the minimax strategy cannot be recommended as a decision rule in general. It represents an extreme risk averse attitude, which does not take into account uncertainties/likelihoods or utilities of different consequences and outcomes. What is a worst case scenario is often difficult to determine; in practice there will always be a need for considerations of likelihood and plausibility. In general, ranking the consequences and outcomes is also difficult.

In general terms, decision analysis addresses tradeoffs between alternatives and conflicting objectives (Clemen, 1996, Keeney and von Winterfeldt, 2001). It provides prescriptions by assessing the uncertainties and the decision maker(s) relative weights for the various attributes (conflicting objectives). More specifically the approach is typically characterized by probabilistic modeling and analysis, and the application of decision rules following the expected utility theory and similar approaches, reflecting the decision maker's values and priorities (Paté-Cornell, 1996). In this way the different alternatives can be ranked. Sensitivity analyses are used to show how strongly the preferred alternative depends on different factors. It is common to consider the results as decision support, but we also see more prescriptive perspectives for which the results are providing 'hard' recommendations for what actions to be taken. In the literature several authors have discussed the application of the precautionary principle in this context (e.g. Keeney and von Winterfeldt, 2001; Graham, 2001). It is concluded that the decision analysis formulation could either agree or disagree with the conclusions of applying the precautionary principle to a specific case. We will return to this discussion linking decision analysis and the precautionary principle in Section 6.1.

3.5. Other issues

One charge against the precautionary principle is that it marginalizes science. However, this charge can be easily refuted when the principle is to be invoked in the case of scientific uncertainties (e.g., Sandin et al., 2002; Rechnitzer, 2020). In such cases, science is not able to provide clear answers. Rather, further research and scientific studies could be the result of weight given to the precautionary principle. As such, the principle stimulates science and scientific work rather than marginalizing it.

However, if the precautionary principle is to cover uncertainties more broadly, this argument against the principle has some rationale. The principle can then easily lead to a weakening of the argumentation and judgments based on existing knowledge, if the scope and ideas of the principle are not properly understood. See also Section 4.

Another argument against the precautionary principle is that it hampers innovation and growth (Miller and Engemann, 2019). Many (risk-reducing) beneficial innovations of the past were only possible because risks had been taken (Zander, 2010, p. 9), and, as noted by Graham (2004, p. 5), technical innovation takes place in a process of trial and error, which would be seriously disturbed by a too strong weight on the precautionary principle.

If a company would like to introduce a new product into the market, the precautionary principle can be interpreted as stating that the company has the burden of proof: demonstrating that the product is safe and the negative risks associated with its use are acceptable. Following this logic, there is initially "a red light which is only switched to green when there is convincing evidence of harmlessness" (Trouwborst, 2016). This perspective represents a stand on the balancing act between development and protection. Too much protection hampers development, whereas too little may lead to accidents, damage and losses.

4. Understanding the precautionary principle using the contemporary risk perspective: Conceptual issues

First in this section we introduce the risk concept and its characterization, based on SRA (2015,2017) and Aven (2016).

See Fig. 1. We consider an activity: for example, the operation of a product or a system, smoking for a person or a population, life in a country or in the world. We are concerned about the potential undesirable consequences of the activity with respect to something of human value. As a general formulation, risk is defined as the combination of

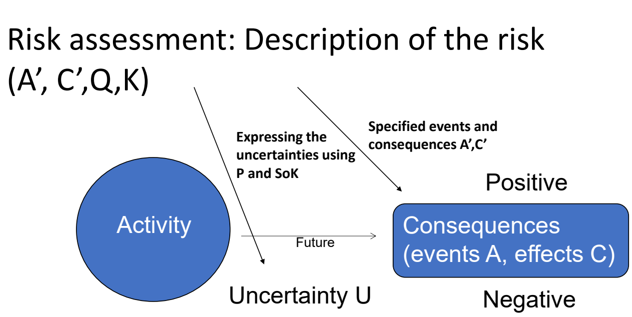

Fig. 1. Illustration of the risk concept (A,C,U) and its characterization (A',C',Q, K), where the measure (description) of uncertainty Q captures probability P (precise or imprecise) and associated strength of knowledge judgments (SoK).

future consequences C of the activity with associated uncertainties U (reflecting that we do not know what C will be), for short denoted (C,U). C is often seen in relation to some reference values, for example 'normal' functioning level, a plan or a goal, and the focus is typically on some negative, undesirable consequences. There is always at least one outcome that is considered negative or undesirable. Alternatively, and without loss of generality, we can write (C,U) as (A,C,U), where A is an event (or a set of events) and C the consequences (effects), given the occurrence of A. The event A represents a hazard, threat or opportunity, as well as risk sources. In the following, we simplify the language and simply refer to A as a threat. Examples of A include failure of a technical unit, the spread of a virus, a fire and a terrorist attack.

In a risk assessment, the risk (A,C,U) is characterized by specifying the threats and consequences, and describing or expressing the uncertainties, leading to a characterization which in generic terms has the form (A',C',Q,K), where A' is the specified events, C' the specified consequences, Q the description of uncertainties about A' and C', and K the knowledge on which the assessment – and particularly Q – is based. It is common to use probability P (precise or imprecise) to express uncertainties, but, following the recommendations in for example SRA (2015,2017), these probabilities should be supplemented with qualitative judgments of the strength of the knowledge (SoK) supporting the probabilities (Flage et al., 2014). The probabilities are subjective (knowledge-based, judgmental (Lindley, 2006). Note that A represents the actual threat occurring, whereas A' represents the thought-constructed threats of the risk assessment. By proper analysis, A' should cover A, but surprises may occur leading to a situation where A is not included in A'.

In relation to the coronavirus, risk captures the occurrence and spread of the virus, with consequences (e.g. loss of lives) and associated uncertainties. A risk characterization specifies what events and consequences to consider, and express uncertainties typically using probability (precise, imprecise, quantitative or qualitative) together with SoK judgments.

To assess the strength of the knowledge, we need to address issues such as (Flage et al., 2014; Aven and Thekdi, 2022):

- The reasonability of assumptions made
- The amount and relevance of data/information
- The degree of agreement among experts
- The degree to which the phenomena involved are understood and accurate models exist
- The degree to which the knowledge has been thoroughly examined

The last point relates to potential surprises and the unforeseen, and covers issues like (e.g., Bjerga and Aven, 2016):

- The possibility of unknown knowns (i.e., others, but not the analysis team, have the knowledge). Have specific measures been implemented to check for this type of event (for example, the use of an independent analysis review)?
- The possibility that events are disregarded because of very low probabilities, although these probabilities are based on critical assumptions. Have specific measures been implemented to check for this type of event (for example, signals and warnings affecting the existing knowledge basis)?
- Risk related to deviations from assumptions made
- Changes in knowledge over time

The analysis addresses the issue that the knowledge could be more or less strong and even wrong.

For others and related schemes classifying knowledge strength, see e.g. Askeland et al., (2017), IPCC (2010) and works based on the so-called NUSAP (Numeral, Unit, Spread, Assessment, and Pedigree) system (Funtowicz and Ravetz, 1990,1993; Kloprogge et al., 2005, 2011; Laes et al., 2011; van der Sluijs et al., 2005a,2005b).

The activity introduced in relation to the risk conceptualization (A,C,U) may be considered for a time period of length T, say, and the consequences C can be associated with this period or longer to also include long-term effects (Logan et al., 2021). Consider, for example, the use of a product observed for a period of 10 years and potential health effects as a result of the use of the product. Although the product is not observed longer than T, the consequences C may extend beyond this period.

The challenge now is to relate the threats and uncertainties of the precautionary principle to the risk, as defined by (A,C,U) and described by (A′,C′,Q,K). When not stated otherwise, the precautionary principle is defined as in SRA (2015):

> 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 (3.1)

This is a definition of the principle according to risk science. It provides a normative obligation, perspective or position for the risk handling which is applied in specific contexts. From a decision analysis perspective, it can be argued that this definition lacks precision as it is not prescribing a clear decision rule for what action to take in specific settings. However, from a risk science perspective, (3.1) is a proper definition as it expresses a basic idea for how to think in relation to risk handling in certain situations.

4.1. Relating the threats of the precautionary principle to risk

Think of a situation where we face risk (A,C,U) and the precautionary principle is considered applied (given weight to). The risk is characterized by (A′,C′,Q,K). Here A′ is referred to as the threat. Following common definitions of the precautionary principle, the threat needs to have the potential for some serious undesirable consequences (for health, the environment). This means that there is a link between the threat and its consequences. As mentioned in Section 3.2, the literature refers to expressions like having credible scientific evidence (data, information, analysis results, test results, modelling insights) of a plausible threat of serious consequences. Following this interpretation, *potential* cannot only refer to thinkable effects, there needs to be some type of risk assessment involved, covering all dimensions of the risk characterization (A′,C′,Q,K).

Suppose the situation is characterized by large uncertainties and weak knowledge. The assessment is then qualitative on a 'high level'. As an illustration, think about the corona virus case of March 2020. Then, it can be argued that governments gave weight to the precautionary principle and implemented strong measures to shut down social life. Here we can think of the threat A' as the occurrence of the virus, or as the occurrence and the spread of the coronavirus. Despite considerable uncertainties about the consequences, judgments were made that the threat was serious – threat scenarios with severe consequences were considered plausible. And there is some evidence supporting this conclusion.

This leads us to a discussion of what plausible means. The issue is thoroughly discussed by Glette-Iversen et al (2022). The authors argue that plausibility in a context like this is to be interpreted as a combined judgment of probability (typically imprecise) and judgments of the strength of the knowledge supporting the probabilities. In line with this understanding, the threat contributing to the invoking of the precautionary principle requires that the risk related to the threat is judged high on the basis of judgment of (A,C,U); i.e., the (A′,C′,Q, K) is considered high, in relation to serious consequences C. As an example, we can think about a judgment made by health experts in a country, stating that the threat is serious, by referring to a likelihood of at least 1 % for several million fatalities and relevant supporting data/evidence/knowledge.

Different criteria can be used in the process of classifying the threat risk as high, for example (Aven and Kristensen, 2019):

(a) The risk is judged to be high when considering consequences and probability
(b) The risk is judged high, considering the potential for severe consequences and significant uncertainty (relatively weak knowledge)
(c) Lack of robustness/resilience
(d) Weak general knowledge about (A,C), including barriers to reduce the negative effects of the event A (the event A here also includes risk sources). A distinction is made between two types of knowledge: 'general knowledge' (GK) and 'specific knowledge' (SK). Using the coronavirus as an example, the former type of knowledge refers to general medical knowledge about viruses, whereas the specific knowledge concerns the knowledge about this specific corona virus.
(e) Weak specific knowledge about (A,C)
(f) Strong general knowledge about undesirable features of (A,C)
(g) Strong specific knowledge about undesirable features of (A,C)

For example, the risk can be classified as *High* if a critical failure on a safety system has been revealed through testing, by reference to (a), (c) and (g). The risk can also be classified as *High* if the safety system has not been tested, with reference to (b), (c) and (e). In the former case, the argument is based on what we know and, in the latter, on what we do not know. In the coronavirus case of March 2020, it can be argued that the criteria (a), (b), (c) and (e) apply.

If the situation is characterized by rather small uncertainties, 'standard threat and risk assessments' can be conducted, providing threat and risk characterizations founded on well established approaches and methods, including Bayesian uncertainty and decision analysis.

4.2. Relating the uncertainties of the precautionary principle to risk

Most definitions of the precautionary principle refer to scientific uncertainties. In the following, the (A,C,U)-(A′,C′,Q,K) risk conceptualization is used to provide possible ways of explaining the concept. In this set-up, uncertainty as a concept refers to a person or a group of persons, not knowing what the consequences of the activity will be (for example related to what events that will occur and when, and their impacts) – it reflects lack of knowledge (SRA, 2015). The uncertainty is described or characterized by (Q,K). Here Q can be quantitative or qualitative, or a combination.

A key question is whether the concept of scientific uncertainties is about the relationship between A' and C', for example expressed by lack of understanding of cause-effect relationships, or about the lack of predictability of the consequences C'. The former case is also about lack of predictability but conditional on the event A'. To illustrate the discussion, let us again return to the coronavirus case. The question then is whether we are concerned about the effects, given the occurrence of the virus, or the occurrence itself is an issue of importance for the classification.

Let us make a thought experiment. Suppose science could predict the consequences C' accurately if A' has occurred, but there are considerable uncertainties about what causes A' to happen and when A' will occur. To be more concrete, think about a system that can fail in only one way, and the effects are known and serious, but we have a complete lack of knowledge about what generates the failure. Would it then be reasonable to talk about scientific uncertainties? Yes, it would, as we do not have strong knowledge about A' (when it will occur and why) and, hence, also about C'. Weak knowledge about the consequences C' means scientific uncertainties about C'. It makes sense to disapprove of a system that could fail because of factors we do not understand, given that the consequences of the failure are severe. If the event A' were to relate to a virus, and the consequences are known and serious, given the occurrence of A', it would make sense to implement measures to reduce vulnerability and strengthen resilience.

It has been suggested that the scientific uncertainty concept should be related to the difficulty of establishing accurate prediction models for the consequences, as mentioned in Section 3.2 (Aven 2011). Let X be a vector of factors influencing the consequences C'. Then, the criterion expresses that we have scientific uncertainties if there is a lack of scientific consensus about an accurate model f(X) linking X and C'. The argumentation in the previous paragraph shows that the factors X need to extend beyond the events typically defined as A'. The relevant phenomena need to be understood, including what causes or leads to the events and consequences. The issue is thus also linked to the way A' is defined. Commonly, A' is used as 'high-level' types of events, like the occurrence of a virus, system failure, flooding, a terrorist attack, etc. The X vector would also relate to underlying factors and sources that could lead to A'.

4.2.1. Interpreting the "better safe than sorry" saying

If the precautionary principle is to reflect the saying "better safe than sorry", it would extend beyond scientific uncertainties. The issue is, then, what type of uncertainties should be included, in addition to scientific uncertainties?

If the only requirement is that the situation is characterized by uncertainties, there will be no limitations on what situations to include, as we always face uncertainties. The issue, then, would be the degree or level of uncertainties and the weight given to the precautionary principle, depending on this level. Hence, one can argue that the situations are standard situations covered by risk management: There are some levels of uncertainty present, but not necessarily scientific uncertainties. In relation to the corona virus case, it can be argued that much of the scientific uncertainties about the consequences C' were removed in the autumn of 2020, yet there was still some level of uncertainty present. Measures were implemented to reduce the consequences and the risks, but it can be discussed to what degree these measures can be justified by reference to the precautionary principle. If a definition like the saying "better safe than sorry" is used, there is a clear rationality, but not so much if the scientific uncertainty is used as a criterion for invoking the principle.

Linking the invoking of the precautionary principle to an uncertainty criterion, as in the saying "better safe than sorry", would make the principle applicable in a huge number of cases, where standard risk management strategies and tools can be used. To distinguish cases of scientific uncertainties – which are in fact quite rare – from these standard settings, it has been suggested to use different terms. For example, Aven and Renn (2010,2018) refer to the precautionary principle, when the criterion is 'scientific uncertainties', and the *cautionary principle* in the general case of uncertainties: If the consequences of an activity could be serious and subject to uncertainties, then cautionary measures should be taken, or the activity should not be carried out (Aven and Renn, 2010, 2018; Aven, 2019a).

The cautionary principle is considered a basic principle of risk management but with a much broader scope than the precautionary principle, which is used only in the case of scientific uncertainties. The need for and justification of both principles in risk management is discussed in the coming section.

5. Understanding the precautionary principle using the contemporary risk perspective: Management issues

A basic acknowledgment in contemporary risk science is the need for seeing beyond analysis, including risk assessments and cost-benefit analyses, when making risk-related decisions (Renn, 2008; SRA, 2017). Such analysis does not *prescribe* what is the right and best decision. The same applies to science in general. Science does not generally prescribe what is the right or best decision. There are two main reasons for this: (1) the analysis is subject to limitations and uncertainties, and (2) people have different values and priorities – we may all agree on the risk related to, for example, nuclear power but conclude differently on whether the risk is acceptable or not.

Risk assessments and other types of analyses inform decision makers. The decision makers will use the information provided and place it in an evaluation and review context, which means summarizing, interpreting and deliberating over the results of the analyses, as well as of other relevant issues (not covered by the analysis), in order to make a decision (Fischhoff et al., 1981; Hertz and Thomas, 1983; Renn, 2008; Aven and Thekdi, 2022). Most analyses are based on assumptions and beliefs, and the decision makers must also consider the relevance and validity of these. Stakeholders' values, preferences, objectives and criteria provide essential input to this evaluation but could also have a strong influence on the definition of the risk problem or issue, as well as on the analyses, in particular when conducting analyses combining risks, costs and benefits (Aven and Thekdi, 2022).

A main goal of risk management is to find the right balance between development and protection. To support protection, the risks related to undesirable events and consequences need to be reduced to an acceptable level. Different principles and measures are used for this purpose. The precautionary and cautionary principles are examples of such principles, and measures strengthening robustness and resilience are examples of such measures. The use of cost-benefit analysis promotes development in this type of analysis, as it is mainly based on expected values, thus giving little weight to the risks and uncertainties.

From this reasoning, no general risk management principle can be formulated as a decision rule. The decision context must always be taken into account, making it impossible to meaningfully define generic rules that specify what to do based on some judgments about risk. Suppose the risk is described by (A',C',Q,K), using the terminology of Section 4. A decision rule could then be based on (A',C',Q,K). However, in the case of scientific uncertainties, the knowledge K is weak; hence, it would not make sense for the decision maker to give much weight to the risk judgments (A',C',Q). If K is stronger, and if the uncertainties are not scientific, more weight can be placed on (A',C',Q), but there will always be a need, as discussed above in this section, for considerations that extend beyond the risk assessment, which are partly analytical (scientific) and partly about values.

For small and moderate levels of uncertainty, analysis could have a strong influence on the decision-making, and placing strong weight on the precautionary/cautionary principle then could be considered in conflict with science and the best knowledge available. Much of the discussion and controversies we see concerning the precautionary principle are rooted in the fact that the term is also used when dealing with moderate levels of uncertainty. Invoking strong precautionary measures without analysis and scientific studies, in such situations, conflicts with the basic principles of risk management and decision analysis. Again, as an example, consider the corona virus case and the use of masks in schools in 2021. To justify this measure, referring to the precautionary principle alone would be problematic, as analysis and science provide rather strong knowledge on the issue. Some actors may give such strong weight to the uncertainties that they conclude that masks in schools should be used, also when taking into account the knowledge available. Their conclusion could be rooted in judgments about the knowledge and uncertainties but also in their values and/or political stands. Thus, it may be difficult to see the impact of the precautionary principle in the risk management decision. Actors may use any type of uncertainties as an argument for giving priority to protective measures. By restricting the scope of the precautionary principle to scientific uncertainties, the application of the principles is made more limited, and the risk of such use can be reduced.

6. Recommended approach. Discussion

Fig. 2 presents an interpretation of the precautionary principle in line with the analysis of Section 4. To give weight to the precautionary principle, two main conditions are needed: (1) the risk threat needs to be considered high, with respect to potential severe consequences of the threat, and (2) the uncertainties need to be scientific. Criterion 1 relies

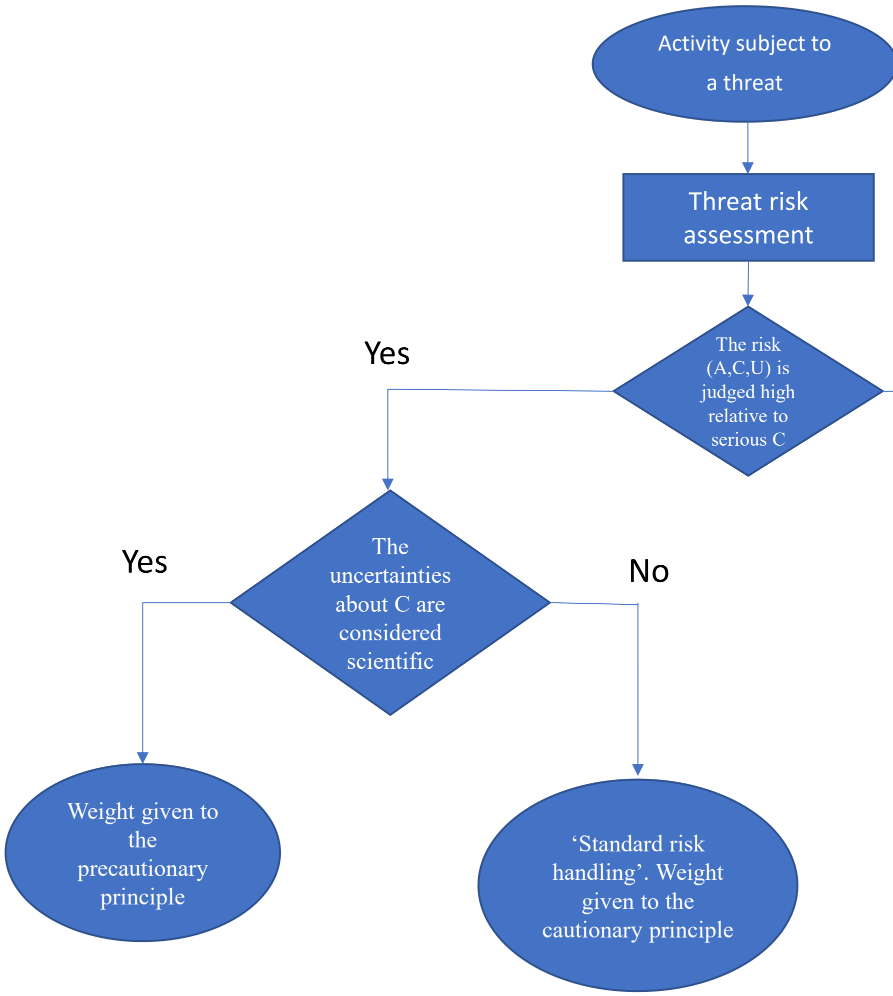

Fig. 2. Model (flow chart) describing when to invoke the precautionary principle.

on a threat risk assessment, which would be qualitative and rather crude, if the uncertainties do not allow for a more detailed quantitative assessment. Criterion 2 is also based on judgments, as there could be different views on what are considered scientific uncertainties. The criterion is linked to the problem of being able to link underlying factors X to C, as discussed in Section 4.2. Applying the precautionary principle allows for considerations of different decision alternatives and measures, and different approaches and methods can be used to support the decision making, including types of decision analysis. These approaches and methods could strengthen the knowledge basis, but cannot be used to prescribe what decision to make as they have limitations in situations characterized by scientific uncertainties.

In case the uncertainties are not scientific, 'standard risk handling' applies, balancing different concerns and using various approaches and methods to support the decision making, including risk assessments, decision analysis and cost-benefit type of analyses. Science supports the decision making. This is in contrast to the case where the uncertainties are scientific, meaning that science currently is not providing strong knowledge about the consequences of the activity. Giving weight to the precautionary principle is justified.

Too much weight on precaution can have negative effects on development. However, too little weight can lead to undesirable consequences for human life and health, and the environment, as history has shown. The precautionary principle plays a role in supporting the latter concern. It is formulated as a principle – a normative obligation or position – a perspective for handling risks of a certain type – whose normative content needs to be linked to the risk handling context. If the decision maker's priorities regarding safety are low, there are ample possibilities to make the principle normatively weak. However, if safety is a main priority, the principle represents a strong instrument for valuing protection, suitably implemented in the context in which it is to apply. In general, decision rules are not easily defined for risk management settings, as they hamper the flexibility needed to take into account the specific conditions of the situation considered.

Even when the knowledge is considered rather strong (the uncertainties are rather small or moderately large), surprises occur. That is why contemporary risk science and management encourage the development and use of a resilient type of arrangements and measures. The cautionary principle gives support to such efforts. Resilience management is today a core strategy of risk management (Renn, 2008; SRA, 2017). Considerable work has been conducted in recent years to develop risk management and governance frameworks that integrate risk assessment-based policies and those of robustness and resilience (IRGC, 2005; SRA, 2017; Aven, 2019b). Risk assessments inform decision makers but have limitations. Not all aspects of risk and uncertainties are taken into account. A key element is the knowledge K that the risk judgements (A',C',Q) are based on. This knowledge could be more or less strong and even wrong. Surprises occur relative to this knowledge. This knowledge is often formulated as assumptions, which means that the risk judgements (A',C',Q) are in fact conditional risk, given the correctness of these assumptions. However, assumptions may turn out to be wrong, and this represents a risk that decision makers also need to take into account. Research has been conducted trying to improve the risk assessments reflecting this risk (e.g., Flage et al., 2014; Berner and

Flage, 2016, 2017; Flage and Askeland, 2020), but it can never be fully analysed, as any analysis would need to be based on some knowledge. The risk management solution is to highlight robustness and resilience, making the system studied able to better withstand and respond to surprising and unforeseen events. This applies in particular to cases characterized by scientific uncertainties.

Different research communities or 'schools' have developed, meeting the challenge of handling such events. One is resilience engineering (management), another, research centred on black swans and related metaphors like 'perfect storms'. Contemporary risk science includes them all as providing valuable input for confronting this challenge in risk management and governance. Yet, we continue to see scientific works, standards and practice that fail to incorporate robustness and resilience-based policies in the risk handling frameworks. An example is the ISO 31,000 guideline on risk management, which builds the risk management on risk assessment, without considerations of robustness and resilience.

6.1. Decision analysis and the precautionary principle

Consider again the corona virus case. The above analysis has argued that authorities' reference to the precautionary principle medio March 2020 made sense when implementing measures to reduce social life: We faced a serious threat A', and the consequences were subject to scientific uncertainties. Waiting to reduce the uncertainties were considered too risky. The thinking aligns with a risk science perspective, but the following discussion will show that it also aligns with decision analysis. Referring to the discussion in Section 3.4, it is of interest to question how a decision analysis approach would relate to the risk science approach giving weight to the precautionary principle as here presented.

Decision analysis can be used for all types of situations, but its strength in informing decision makers depends strongly on the case considered. There will always be some knowledge available that should be used to guide the decision makers. Both risk analysis and decision analysis provide tools for how to represent and express this knowledge (Paté-Cornell, 1996; Engemann and Miller, 2017, 2022). The focus is here on situations characterized by scientific uncertainties, and then any analytical approach is struggling providing timely, informative decision support. Models used will necessarily be based on highly uncertain assumptions and the probabilities assigned will have a weak knowledge basis.

To be concrete, let us again return to the corona virus case medio March 2020. The situation can be characterized by scientific uncertainties; accurate prediction models are not available. Still risk and decision analyses were conducted, but these had strong limitations due to the large uncertainties. To illustrate, think about a probabilistic analysis leading to say a 90% prediction interval of 10,000–20,000 fatalities in a country under some specific assumptions, and less than 1% probability for more than 100,000 fatalities, if not strong measures are implemented to shut down social life. Depending on the measures introduced, the fatality numbers are expected to be significantly reduced. The decision makers will not, however, give much weight to these assessments because the knowledge supporting them is weak. The uncertainties are large and there is a potential for considerable deviations from the predictions made. The decision makers need to take into account this potential, including potential surprises and unforeseen types of development of the epidemic.

Seeing the analyses as decision support, there is no conflict between the analyses and the application of the precautionary principle. Following a risk science rationale, governments medio March 2020 gave weight to the precautionary principle, recognizing that the countries were faced with a serious threat where the consequences were subject to scientific uncertainties. The risk and decision analyses provided input to the decision-making process and which measures to implement. The results of these analyses as well as other factors, including political ones, led to different weight given to the precautionary principle and what measures to implement. As an example, think about the difference in policies among the Nordic countries. All countries implemented some precautionary measures, but only Denmark, Finland, Island and Norway imposed what can be seen as a societal shutdown (however, not all functions where shut down - for example, critical infrastructures were kept open). However, these four countries opened up again many activities – for example schools - after some few months when obtaining new knowledge about the virus and its effects. To large extent the knowledge basis – the risk and decision analysis basis – in these five countries were similar, yet the policies were different. It can be argued that Sweden gave less weight to precautionary principle than the other four countries.

It is always difficult to evaluate risk decision with hindsight, but it is interesting to note that Sweden observed a very high number of corona virus deaths Spring 2020 compared to the other four countries – most linked to elderly care homes. The motivation for applying the precautionary principle is exactly this, to introduce measures to avoid extreme outcomes and at the same time allow more knowledge to be gained and the uncertainties being reduced. The problem is of course in general that we do not know in advance what will be the consequences of the decisions made, as the uncertainties are large.

Above we have limited the analysis discussion to understanding the risks. Decision analysis goes one step further and also tries to guide decision makers what is the proper decision, reflecting the decision makers values and priorities. Provided that the analyses are seen as tools to gain insights and decision support, this type of analyses does not change the above reasoning. Decision analysis support the decision makers in making proper decisions, and its input is balanced against other concerns and factors, including the weight to be given to uncertainties and the precautionary principle. Decision analysis methodologies provide a means of assessing the decision situation, by structuring the problem with its decision alternatives, stakeholders and uncertainties, see for example Keeney and von Winterfeldt (2001) and Miller and Engemann. (2019).

However, if decision analysis is used as a prescription for what action to take, there is potentially a conflict between decision analysis and application of the precautionary principle. The rationale for such a prescriptive approach to decision analysis in situations characterized by scientific uncertainties is, however, difficult to see, refer discussion in Section 5.

In Section 3.4, the minimax decision making strategy was referred to. The corona virus case illustrates why this strategy is not consistent with the precautionary principle. To simplify, suppose we consider only three decision alternatives: full shut down of the society, partial shutdown (as in Denmark, Finland, Island and Norway), or not shut down (as in Sweden). And let us focus on the number of deaths. The authorities in a country specify a worst case for these alternatives as say 1000, 2500, and 10,000, respectively. The minimax rule then states that the full shut down alternative should be selected as it minimizes the maximum. As mentioned above, these countries' policies were partial shutdown or not shutdown. The minimax strategy would always support the decision alternative with the worst consequences which is not what the precautionary principle expresses. Rather the principle gives rise to considerations balancing different concerns, not assuming the worst and restricting attention to only health and environmental issues.

Think of a game with two decision alternatives, playing the game or not, with the game resulting in either a reward or a loss. The reward is 1000 euros whereas the loss is unknown to you. The outcome is determined by throwing a fair coin. The conditions for applying the precautionary principle are met - the consequences could be serious and they are subject to scientific uncertainties. Hence measures should be implemented or the game should not be carried out. The precautionary principle does not conclude that the game should not be carried out. Following the minimax strategy that conclusion would always be the answer. Rather the precautionary principle would promote considerations of measures to reduce the uncertainties, leading to a more informed decision. Hence the principle can stimulate research and analysis. A key issue is the time available to reduce the uncertainties and improve the decision basis (refer discussions in e.g. Keeney and von Winterfeldt 2001, Graham 2001). In the corona virus case, time was considered critical medio March 2020, but in other cases there could be possibilities to defer the decision making. Then risk and decision analysis represent key tools to strengthen the decision basis.

Decision analysis discusses many types of decision-making strategies, closely related to minimax, for example minimax regret and the 'comfort approach' (see Rechnitzer 2020, Engemann, and Yager 2018. Engemann and Miller 2022). These strategies meet some of the challenges of the minimax strategy, but the conclusions made above concerning the precautionary principle are the same: These strategies would select the decision alternative on the basis of a formula based on specified consequences, which is not what the precautionary principle expresses. The precautionary principle allows for considerations balancing different concerns, reflecting also uncertainties. The minimax regret and the 'comfort approach' require specification of cardinal utilities, which is not necessary in order to apply the precautionary principle.

For situations where the precautionary principle is applicable, multi-attribute analysis is often the most suitable type of decision analysis method. Using this method, the consequences of the various decision alternatives are addressed separately for the various attributes of interest. For some attributes, quantitative analyses may be informative, while for others, qualitative analyses are more appropriate. No attempt is made to transform all the different attributes into one comparable unit. The decision-makers have to implicitly weigh the different attributes, in the decision makers evaluation and review.

6.2. *The insights gained*

Table 2 summarizes the new knowledge obtained by the present work. The paper has two main contributions; the first relates to enhanced understanding of the rationale of the precautionary principle, the second to the enhanced understanding of the relationship between the precautionary principle and decision analysis and decision analysis methods. The new insights are obtained by building on contemporary risk and safety science knowledge. The common perspective for discussing the conditions for applying the precautionary principle has been probability-based perspectives on risk in contrast to the current analysis where uncertainty is a main component of risk. The uncertainty-based perspective allows for an improved understanding of the conditions invoking the precautionary principle, in particular related to the threat and uncertainty dimensions. A key point is that the principle requires a crude qualitative threat risk assessment - capturing the elements (A',C', Q,K) - to make a judgment about the severity of the threat, where uncertainty and knowledge are central aspects to consider. The saying "better safe than sorry" is commonly linked to the precautionary principle, but it is not consistent with the precautionary principle when this principle is restricted to scientific uncertainties. The present paper argues that such restrictions are required to adequately use the principle. Much of the disputes we see concerning the precautionary principle can be traced back to the fact that the principle is used for all types of situations, also when considering moderate levels of uncertainties and probabilities can be supported by rather strong knowledge bases. In such situations, scientific analysis should guide the decision making. The scientific literature acknowledges the importance of seeing risk and decision analyses as decision support and not as prescriptive tools for what to do. Yet there is a need for stressing the rationale for the decision makers review and evaluation, to ensure that due considerations are given to factors not covered by the analyses. The societal shutdowns medio March 2020 were based on such reviews and evaluations, with input from health experts. It can be argued that the Swedish Government did not conduct such reviews and evaluations to the same degree as in the other Nordic countries (Brusselaers et al., 2022; Ludvigsson, 2023).

The precautionary principle is commonly considered in line with the minimax decision analysis strategy (Gardiner, 2006; Aldred, 2012). The present paper supplement earlier discussion strenghtening the argumentation why this is not the case, also including related strategies such as minimax regret and the 'comfort approach'. Seeing decision analysis as a decision support tool, there is no conflict between decision analysis and the precautionary principle. Unfortunately, in case of scientific uncertainties, risk assessments and decision analysis have strong limitations in providing such support.

Table 2
Main scientific contributions of the paper.

Contribution	More detailed explanation
An enhanced understanding of the rationale of the precautionary principle by using contemporary risk science knowledge	Improved explanation of how risk and its main features are linked to the precautionary principle and the conditions for invoking the principle (Sections 4–6)
	Clarification of what the conditions are for invoking the precautionary principle, in particular in relation to the understanding of the threat concept (Section 4)
	Clarification of the difference between the threat definition as an event or a risk source, and the threat risk assessment to make a judgment about the severity of the threat addressing also uncertainties (Section 4.1)
	How the saying "better safe than sorry" relates to the precautionary principle (Section 4.2.1)
	Enhanced reasoning on the need for decision makers' evaluation and review, extending beyond the analysis and scientific knowledge (Sections 5 and 6)
An enhanced understanding of the relationship between the precautionary principle and decision analysis and decision analysis methods	Improved reasoning why decision analysis and science in general are not in conflict with the precautionary principle (Section 6.1)
	Further clarifications of why the minimax decision rule (and related rules) is not consistent with the precautionary principle (Section 6.1)

7. Conclusions

This paper has aimed at providing new insights about the precautionary principle, by applying a risk science perspective to the criteria invoking the principle. The paper concludes that the precautionary principle – as other general risk management principles – can be justified as a fundamental principle expressing a normative obligation, position or perspective, but not as a decision rule prescribing what to do. More specific procedures, standards and directives can, however, be derived, implementing the ideas of the precautionary principle in concrete contexts. The principle should be restricted to the case of scientific uncertainties, to avoid it being confused with the idea of giving weight to uncertainties in general to adequately handle risk. The principle applies when facing a serious threat, which means that a crude threat risk assessment needs to be conducted. This assessment, as well as the judgment made that one faces scientific uncertainties, depends on the available knowledge, as well as on the assessors. Invoking the precautionary principle is thus not a scientific issue but subjective and dependent on the decision makers' values and preferences. The precautionary principle is not in conflict with decision analysis and science in general. Such analysis and scientific work can provide useful decision support, guiding what precautionary measures to be implemented and when. The principle points to the need for giving timely and due attention to risky situations characterized by scientific uncertainties, but does not prescribe how this is best to be done. The decision making needs to take into account current knowledge and strengthen the knowledge base to the degree possible.

CRediT authorship contribution statement

Terje Aven: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

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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