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The concept of plausibility in a risk analysis context: Review and clarifications of defining ideas and interpretations

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ABSTRACT

The plausibility concept has gained increasing attention in recent years in risk analysis settings. A number of definitions exist, most of which interpret plausibility as an expression of uncertainty. The concept is frequently referred to in scenario analysis and emerging risk contexts, which are characterized by large uncertainties. The difficulty of assigning probabilities in such cases has led some to claim that, by offering a purely qualitative approach, plausibility is a more suitable tool for measuring uncertainty. However, a proper clarification of what the plausibility concept means in a risk analysis context is missing; current definitions of the concept do not provide a clear understanding of how plausibility is linked to fundamental aspects of risk and uncertainty. The present paper aims to rectify these issues, by i) reviewing and discussing how the plausibility concept is interpreted and used in the literature, ii) providing a suggested interpretation of the concept in a risk analysis context, and iii) giving our recommendations on how the practical application of the plausibility concept can be enhanced by drawing on contemporary risk science, specifically with regard to highlighting the likelihood and knowledge dimensions of risk. Based on the review, it is shown that the concept of plausibility should be seen as a measure of uncertainty capturing a combination of likelihood and judgments on the supporting knowledge. We conclude that a prudent use of the concept requires that each of these dimensions are addressed explicitly, using imprecise probabilities and strength of knowledge judgments.

1. Introduction

Addressing uncertainty about the future is a fundamental issue within the risk field. However, risk analysis is not the only discipline providing knowledge on this topic; there are a number of schools with a focus on developing suitable approaches and methods for assessing and describing uncertainty. Examples of such are scenario analysis and future studies (van der Helm, 2006) and post-normal science (Ravetz, 1999). Frameworks for representing uncertainty provided by these schools are specifically directed towards contexts where uncertainties are large, making them particularly relevant for risk problems characterized by high complexity and interconnectivity. Emerging risks and systemic risks are examples of such risk types, a common feature of which is high uncertainty and a fundamental lack of knowledge, making cause-effect relationships difficult to establish (IRGC, 2015, 2018).

In literature related to scenario analysis and future studies, plausibility is "heartily raised (…) and in nearly all explanations of scenario planning it is named as a criterion for good scenarios" (Selin and Guimarães Pereira, 2013a, p. 95). However, according to the IPCC (Intergovernmental Panel on Climate Change) definition of a scenario, which is widely used and referred to in scientific literature, plausibility is not only a criterion for evaluating the 'goodness' of scenarios, but an inherent feature of scenarios as a concept: "A scenario is a coherent, internally consistent and plausible description of a possible future state of the world" (IPCC, 2001, p. 26). The concepts of emerging risk and systemic risk can be linked to scenario analysis, partly by the guidelines provided by the International Risk Governance Council (IRGC), in which scenario development constitutes a central feature in the recommended approaches to identifying and managing these types of risks (IRGC, 2015, 2018). Consequently, by serving as a key concept for scenario practitioners, plausibility has also become a prevalent measure of uncertainty in contexts involving emerging risks and systemic risks. The plausibility concept is also used in relation to the precautionary principle. In a report presented in 2005, the World Commission on the Ethics of Scientific Knowledge (COMEST) refers to the principle as follows: "When human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm" (COMEST, 2005, p. 14). In the post-normal science

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framework for managing and communicating uncertainty, NUSAP, plausibility is a criterion when assessing pedigree (see e.g. Boone et al., 2010; van der Sluijs et al., 2005), thus relating the concept of plausibility to the quality or strength of the background knowledge supporting the uncertainty/risk assessment. As a final example, plausibility is a key component in Dempster-Shafer theory (Shafer, 1976), also known as evidence theory or the theory of belief functions. In this theory, which is sometimes presented as a generalization of Bayesian theory of subjective probability, a pair of functions – a belief function and a plausibility function – are used to measure the uncertainty of an event.

As seen from the examples above, the plausibility concept is referred to and applied in a number of different settings. The main issue addressed in the present paper is the lack of a conceptual foundation supporting these applications. When scrutinizing the interpretations found in the literature, several deficits are identified. Firstly, many of the current definitions refer to other concepts – which are equally hard to define – to explain what plausibility means. For example, Wiek et al. (2013) define plausibility as "the quality of a scenario to hold enough evidence to be qualified as 'occurrable', i.e., to become real, to happen" (2013, p. 138). Similarly, Nordmann (2013) holds the term 'plausible' equivalent to 'seriously possible'. However, what is meant by 'occurrable' and 'possible' is not straightforward, and deploying these terms to define plausibility leaves room for many different interpretations. Moreover, some of the interpretations relate to judgments of plausibility, or plausibility perceptions, rather than the concept per se. An example is Lombardi et al. (2013), who define plausibility as "a judgment on the relative potential truthfulness of incoming information compared to our existing mental representations" (2013, p. 50).

The many different interpretations and practical applications of this concept lead us to question: What does plausibility actually mean in a risk and uncertainty context? Is plausibility a qualitative representation of uncertainty? Is it referring to the quality or strength of knowledge, as indicated by, for example, the NUSAP framework? Or is plausibility a mixture of these two, a way of combining uncertainty representations and strength of knowledge judgments? Several attempts have been made to clarify the meaning of the plausibility concept, inter alia two conferences in 2009 and 2012, the latter of which resulted in a special issue on plausibility in the *International Journal of Foresight and Innovation Policy* (Selin and Guimarães Pereira, 2013b). Still, the interpretations found in the existing body of literature do not provide clear answers to these questions – an operational definition of the concept of plausibility is missing. The paper aims to rectify this by reviewing and analysing current definitions of plausibility in light of contemporary risk perspectives where uncertainty is highlighted as a key component (SRA, 2015, 2018). Based on the analysis, we will provide a suggested interpretation of the concept of plausibility, as seen from a risk science context.

In the face of large uncertainties, a fundamental question raised is: Should we enhance the probabilistic thinking to make it suitable for uncertainty characterizations in these contexts, or should we explore alternative approaches? Proponents of plausibility lean towards the latter, often taking a critical stance towards the use of probability or what Selin and Guimaraes Pereira (2013a) refer to as "the 'future' [being] perversely tamed into numbers with prediction and probability shielding complexity and uncertainty" (2013a, p. 96). Several issues are raised against the use of probability – the difficulty of assigning probabilities in cases where knowledge is incomplete, lack of accuracy, and misleading assumptions that are not made transparent – all of which result in the inability to provide authoritative guidance to decision-makers (Selin and Guimarães Pereira, 2013a). These issues are legitimate to raise, they are well known to many of those who are familiar with the use of probability as a measure of uncertainty. A strong body of literature has been produced, addressing these very issues in relation to the concept of probability. However, we question whether the concept of plausibility is supported by a similar scientific foundation, allowing for the issues stated above to be confronted. For example, how is the background knowledge supporting the plausibility judgments reflected? Are there methods and approaches for scrutinizing this knowledge, revealing gaps in which surprises could be concealed? And how are these reflections conveyed to decision-makers? The objective of the present paper is to reflect on how such issues can be resolved, by conducting a thorough analysis of the current interpretations and use of the plausibility concept and providing some insights on how principles and methods from risk science related to uncertainty assessment can contribute to improving the understanding and application of the concept. These principles and methods address issues on inter alia how uncertainty can be assessed using a combination of qualitative and quantitative tools, where the emphasis is on characterizing the strength of the knowledge supporting the assessments, as well as the identification of potential surprises.

The remainder of the paper is organized as follows. Section 2 provides a review of current interpretations and use of the plausibility concept found in the scientific literature, following up the brief overview above. In Section 3, we discuss some of the key findings from the review in Section 2. Then, in Section 4, we discuss how the understanding and practical application of plausibility can be enhanced by incorporating views on uncertainty assessment based on prevailing risk science theory, particularly concerning the aspects of likelihood and knowledge, and how these dimensions are reflected in the uncertainty judgments. Some conclusions are drawn in Section 5.

2. Review of current definitions and use of the plausibility concept

The review in the next subsections addresses definitions of plausibility and practical applications of the concept, respectively.

2.1. Definitions of plausibility

A selection of definitions and interpretations of the plausibility concept found in the scientific literature is listed in Table 1. The aim is not to provide an exhaustive overview of definitions but to draw attention to some of the most common interpretations of plausibility. The chosen sample is considered sufficient for this purpose.

Plausibility is not a trivial concept to define, and, as seen from the list of interpretations in Table 1, there is a range of notions on what the concept actually represents. In the following section, a structured overview of the interpretations will be provided by systematizing the basic ideas and notions of plausibility conveyed in the definitions.

According to some of the definitions, the concept of plausibility designates the degree to which a statement or event can be considered credible (Van der Helm, 2006), consistent (Connell and Keane, 2006), coherent (Fischer and Dannenberg, 2021) or in accordance (Boone et al., 2010) with existing world views (prior information, beliefs, theories, based on historical data etc.). This interpretation of plausibility links the concept to assessments of how well a statement or narrative about the future corresponds with our current knowledge. Connell and Keane (2006) refer to this as the 'knowledge-fitting theory', stating that "a highly plausible scenario is one that fits prior knowledge well" (Connell and Keane, 2006, p. 95). Consider, for example, the event that the computer system in an organization is hacked (referred to as event A1). The plausibility of such an event, according to this notion of the concept, can be interpreted as a representation of the degree of belief we have in the event A1 occurring, given our foundation of knowledge (what we know about the phenomena involved, historical data on previous hacker attacks, information on possible security gaps in the system, etc.) Thus, we are led to considerations strongly resembling subjective judgments of likelihood. In this context, a subjective likelihood can be considered equivalent to a subjective probability, suitably interpreted. The review shows that interpretations are often lacking, although risk science and current risk perspectives point to several definitions (SRA, 2015; Flage et al. 2014). The present authors consider the following interpretation

Table 1
Definitions and interpretations of 'plausibility' found in the literature. Category I: Plausibility is interpreted as a measure of likelihood Category II: Plausibility is interpreted as a measure of knowledge strength.

Source	Definition of 'plausibility'	Category of interpretation
Oxford English Dictionary	"The quality in an argument, statement, etc., of seeming reasonable or probable; appearance of reasonableness; believability, credibility"	I, II
Boone et al. (2010, p. 340)	"The plausibility criterion designates the degree, mostly based on intuitive assessment, to which an assumption is in accordance with the 'reality'."	I
Bosch (2010, p. 387)	"A theory may, then, be accepted as plausible when it is in accordance with (practical) empirical findings; subjective/intersubjective ideas, thoughts, and feelings; and the opinions of and cultural categories used by others."	I
Connell and Keane (2006, p. 96)	"Although plausibility has not been well explained in the existing literature, there is a rough consensus that it has something to do with the coherence of concepts based on prior knowledge. This view holds that some concept, scenario, event, or discourse is plausible if it is conceptually consistent with what is known to have occurred in the past."	I, II
Fischer and Dannenberg (2021)	"(…) plausibility is creating coherence both within a future, and with regard to its developmental path from the present, on the basis of conformity to prior knowledge and respective worldviews."	I
Janasik (2021)	"To say that plausibility 'is precision' is to say that that it is a measure of the confidence that we have in prior information (beliefs, probabilistic predictions) about the world."	II
Lombardi et al. (2013, p. 50)	"We define plausibility as a judgment on the relative potential truthfulness of incoming information compared to our existing mental representations."	I
Lombardi et al. (2016, p. 35)	"By plausibility we mean what is perceived to be potentially truthful when evaluating explanations."	I, II
Morgan and Keith (2008)	Plausibility is a synonym for relative subjective probability	I
Nordmann (2013)	Plausibility is equal to serious possibility	I
Nussbaum (2011, p. 90)	"A proposition is plausible if it is reasonable to accept the proposition."	II
Ramírez et al. (2017, p. 6)	"By plausible, we mean that [the scenarios] should be neither too improbable nor too familiar."	I
Ramírez and Selin (2014, p. 59)	"Probability has thus come to measure belief, whereas plausibility simply proposes it."	I
Schmidt-Scheele (2020, p. 217)	"(…) a scenario is plausible if high credibility perceptions of the scenario itself and/or its methods exist, if the scenario matches with users' own ideas about the subject matter, and is furthermore dependent on the activation of several commonly known cognitive heuristics."	I, II
Sinatra and Lombardi (2020, p. 124)	"Plausibility is an epistemic judgment about the potential truthfulness of a claim."	I
Van der Helm (2006, p. 26)	"Plausibility refers to the structure of the argument, where truth-value is based on the convincingness, the credibility, of the discourse describing the future."	I, II
Wiek et al. (2013, p. 138)	"(…) plausibility is the quality of a scenario to hold enough evidence to be qualified as 'occurrable', i.e., to become real, to happen."	I, II

most appropriate for the applications here considered (Lindley 2006): assigning a subjective likelihood/probability of, say, 0.1, to an event means that the assessor has the same degree of belief for the event occurring as drawing a particular ball out of an urn containing 10 balls in total.

Notably, the term 'likelihood' is rarely referred to when studying current definitions of plausibility. Rather, we find referrals to other terms indicating a similar notion, such as 'truth-value' (Van der Helm, 2006) and the 'potential truthfulness' (Sinatra and Lombardi, 2020) of claims. However, in a risk and uncertainty context, the use of such terms is problematic; we are referring to the truth about some future scenario or event, but, at the present point in time, the truth about the future is unknown.

A focal aspect of several discussions on the meaning of plausibility, also reflected in some of the definitions listed in Table 1, is the juxtaposition of plausibility against concepts like probability and possibility. There are, however, different views on how these concepts relate. According to Ramírez and Selin (2014), probability measures belief, while plausibility only proposes it. We struggle with this distinction; if both concepts are interpreted as measures of the degree of belief in an event or scenario occurring, the difference between measuring belief and proposing it may simply be understood as stating different *levels* or *degrees* of belief. This line of reasoning leads us to the perspective held by some scholars: that plausibility and subjective probability are, in fact, equivalent concepts;

> "The literature on scenarios often aims to make a sharp distinction between scenarios and forecasts or projections; for example, it is asserted that scenarios are judged by their 'feasibility' or 'plausibility' rather than their likelihood. We cannot find any sensible interpretation of these terms other than as synonyms for relative subjective probability" (Morgan and Keith, 2008, p. 196).

Wiek et al. (2013) claim that the equivalence between plausibility and probability holds in one direction: "if a scenario is deemed highly probable, it follows that the scenario will also be considered highly plausible. However, in reverse, plausibility does not require the explicit assignment of probabilities" (Wiek et al., 2013, p. 137). Another perspective on the relationship between probability, plausibility and possibility is offered by Urueña (2019), suggesting that 'the plausible' is situated beyond the scope of 'the probable', whilst serving as a limiting tool on the broad space of what is considered 'the possible'. According to this reasoning, "A plausible scenario in a given world is presupposed to be possible in the same world. In the same way, a probable future scenario in a given world is presupposed to be plausible (and, therefore, also possible) in the same world" (Urueña, 2019, p. 20). However, some scholars question this notion of plausibility. For example, Van der Helm (2006) claims that, as plausibility refers to the credibility or convincingness of a statement based on our current beliefs, we may create "a convincing description of a future, which we can hold true, even though this future itself can be factually fallacious" and, thus, "A future can be plausible without being possible" (van der Helm, 2006, p. 26). According to Nordmann (2013), plausibility is the same as 'serious possibility', associating this term with what can be considered credible within a world. In relation to this notion of plausibility, probability is defined as "anything seriously possible to which a probability-measure can be assigned" (Nordmann, 2013, p. 127). However, subjective probabilities can always be assigned (although the knowledge supporting the judgments could be more or less strong); thus, the rationale supporting such a distinction can be questioned.

Another line of thinking is found in the definition by Janasik (2021), who interprets plausibility as a measure of the confidence we have in prior information. Hence, the concept is related to the quality/strength of knowledge judgments. The relationship between plausibility and quality of knowledge is made explicit by Selin and Guimaraes Pereira (2013a), stating that "Plausibility relates directly to the quality of

knowledge produced in realms where facts are uncertain, undetermined or even unknown" (2013, p. 100). Furthermore, they link this perspective to the etymology of plausibility; the term 'plausible' goes back to the 16th century, originating from the Latin phrase 'plausibilis', in the sense 'deserving applause or approval'. The knowledge aspect is also covered in the 'knowledge-fitting theory' by Connell and Keane (2006), where the degree of plausibility is determined by three components, all of which can be interpreted as assessment criteria reflecting the quality or strength of the supporting knowledge: "A scenario will be perfectly plausible only if its representation has minimal *complexity* and *conjecture*, and/or maximal *corroboration*" (2006, p. 99). A similar notion of the concept is found in relation to the NUSAP framework, in which plausibility is used as a criterion for assessing 'pedigree', i.e. for reviewing the knowledge base of assumptions (see e.g. Van der Sluijs et al., 2005; Boone et al., 2010). Following this reasoning, the concept of plausibility can be seen as a tool supporting the uncertainty judgments, by providing reflections on the foundation of the knowledge that the assessment is built on and evaluating whether the assumptions made can be considered reasonable or justified. The notion of plausibility as a means of providing support to assessments of uncertainty is also reflected by Tversky and Kahneman (1973), who state that "The plausibility of (…) scenarios, or the ease with which they come to mind, can provide a basis for the judgment of likelihood" (1973, p. 228).

Summarizing the above review, the interpretations of plausibility can be roughly divided into two categories: The first (referred to as category I) constitutes the definitions that relate plausibility to the level of consistency with current knowledge, i.e. how well an event or scenario fits our beliefs about the world. From this perspective, plausibility is understood as a measure of likelihood, often placed in some sort of collocation with concepts like probability and possibility. The definitions by Van der Helm (2006) and Wiek et al. (2013) are examples of interpretations belonging to this category.

The second category (referred to as category II) represents the interpretations that associate the concept of plausibility with the quality or strength of the knowledge supporting the assessment, as seen in the definition by Janasik (2021), as well as the understanding of plausibility in relation to the NUSAP framework.

Furthermore, there are notions of plausibility in which we find referrals to elements from both categories, for example in the following statement by Urueña (2019): "Discussing on plausibility entails to collectively identify and embrace the uncertainties, assumptions, expectations, and hopes about the future that we actually have, and reflect on the robustness of the reasons that support them" (Urueña, 2019, p. 22). Similarly, in the model of plausibility put forward by Connell and Keane (2006), the concept is related to a combination of the interpretations found in categories I and II, where assessments on the quality/strength of knowledge are used as a tool to support plausibility judgments.

2.2. Plausibility used in practice

As mentioned in the introduction, the concept of plausibility is often referred to in contexts where uncertainties are large. It is argued that "where predictive capacity is limited due to high uncertainty from systemic and temporal complexity", plausibility allows us to "explore futures which are improbable (or unlikely) but could still occur" (Wiek et al., 2013, p. 137). Consequently, plausibility serves as a key concept for several essential and highly influential principles and approaches related to the fields of risk and uncertainty analysis. For example, COMEST (2005) refers to the concept in its definition of the precautionary principle, asserting that the principle is applicable in cases where "human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain" (2005, p. 14). Similarly, the UK Health and Safety Executive (HSE) deploys the plausibility concept in its interpretation of the precautionary principle, stating that the 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" (HSE, 2001, p. 29). Hence, plausibility becomes a key criterion in relation to the meaning and use of the precautionary principle.

In addition to featuring in several influential definitions of the precautionary principle, plausibility is frequently referred to in scenario analysis settings. The concept has become particularly prevalent within the so-called "intuitive logics" school, a widely used approach to scenario analysis whose "distinctive characteristic (…) is that it explicitly considers probability to be irrelevant in scenario work and uses plausibility precisely because it considers scenarios are used in situations where probability cannot operate and forecasting is impossible" (Ramírez and Selin, 2014, p. 61). Wilkinson et al. (2013) suggest that plausibility-based scenario approaches are particularly useful in situations characterized by high uncertainty and complexity. Furthermore, plausibility-centred approaches to scenario development have been brought to the fore as a suitable practice for managing risk problems such as systemic risks and emerging risks. For example, in relation to the governance of emerging risks, the IRGC suggests using explorative scenarios that "focus on the construction of plausible sequences of events where present threats and opportunities may become risks to be managed or competitive advantages to be pursued" (IRGC, 2015, p. 27). Similarly, for systemic risks, it is stated that

> (…) qualitative exploratory scenarios of plausible futures (narratives, or storylines) can be equally useful in exploring various scenarios 'in play' in a complex interconnected system, as well as in identifying goals for how one would like a system to operate under shock or stress. They can be a key feature of effective preparedness for future development of systemic risks (…) (IRGC, 2018, p. 25).

The inclination towards a plausibility-based perspective on scenario analysis has been adopted by the IPCC in its work on developing climate and emission scenarios, where the practical approach to scenario analysis implies "steering clear of allocating probabilities and focusing instead on the plausibility of the scenario set" (Wilkinson et al., 2013, p. 706). Notably, plausibility constitutes an inherent property of scenarios, according to the IPCC definition referred to in the introduction ("A scenario is a coherent, internally consistent and plausible description of a possible future state of the world" (IPCC, 2001, p. 26)).

3. Discussion

The review from Section 2 shows that there are different notions of what the concept of plausibility means or represents. Several of the interpretations from Table 1 define plausibility with reference to concepts and terms such as 'conceptual consistency', 'credibility', 'possibility' and 'coherence'. However, what is meant by a statement or an event being 'credible' or 'coherent' is not intuitive, and these terms could be subject to different interpretations. As an example, in their review of the concept of credibility, Hilligoss and Rieh (2008) note that "Credibility has been defined as believability, trust, reliability, accuracy, fairness, objectivity, and dozens of other concepts and combinations thereof" (2008, p. 1468). When such non-trivial concepts are deployed to define plausibility, yet no interpretation is provided to clarify what these concepts mean, a clear understanding of plausibility is difficult to obtain.

When discussing how the understanding of plausibility can be clarified, Urueña (2019) distinguishes between two essential questions: "The first question relates to the theoretical-conceptual basis of plausibility (i.e., 'What does plausibility refer to?'), and the second question relates to its operationalization for evaluating scenarios (i.e., 'How can and should the plausibility of a scenario be assessed and determined?')" (2019, p. 16). It can be argued that several of the definitions from Table 1 focus on the latter question, leaving the former question unaddressed. For example, Schmidt-Scheele (2020) states that "a scenario is

plausible if high credibility perceptions of the scenario itself and/or its methods exist, if the scenario matches with users' own ideas about the subject matter and is furthermore dependent on the activation of several commonly known cognitive heuristics" (2020, p. 217). A similar perspective is found in the interpretation by Bosch (2010), who asserts that: "A theory may, then, be accepted as plausible when it is in accordance with (practical) empirical findings; subjective/intersubjective ideas, thoughts, and feelings (…)" (2010, p. 387), as well as in the work by Connell and Keane (2006), where it is stated that "some concept, scenario, event, or discourse is plausible if it is conceptually consistent with what is known to have occurred in the past" (2006, p. 96). These definitions provide guidance on how to determine whether an event, theory or scenario is plausible or not, based on some given criteria. They prescribe how to conduct plausibility judgments, but what these judgments actually convey remains unclear, as an overall definition of the plausibility concept is missing. As noted by Van der Helm (2006), "There is no added value in the claim that some future is plausible (or probable, or possible), if there is no meaning given to plausibility (or probability, or possibility) itself" (van der Helm, 2006, p. 26).

Some of the reviewed definitions refer to plausibility as a measure of likelihood (classified as category I interpretations in Section 2.1). Adopting such a perspective requires some essential properties of plausibility to be clarified. Firstly, is plausibility subjective or objective? This should be considered a primordial aspect of any tool used to express likelihood, but the definitions of plausibility from Table 1 do not provide a clear answer to this question. There are, however, several statements from the literature indicating a subjective interpretation. For example, Selin and Guimaraes Pereira (2013a) assert that "plausibility is not intrinsic in something but it is about the work that goes into the claims" (2013, p. 94). Similarly, Van der Helm (2006) states that "plausibility is a purely subject-related notion: plausibility cannot exist other than through the fact that it is carried by human reasoning. In other words, something can only be plausible when someone claims it to be" (2006, p. 24). Furthermore, the understanding of plausibility as a subjective measure is supported by the link to subjective probabilities (Morgan and Keith, 2008), as well as through the interpretation of plausibility as a measure of the degree or level of belief (Ramírez and Selin, 2014). Clearly, the overall notion of plausibility justifies a subjective interpretation. However, this interpretation is not made explicit in current definitions of the concept, and, thus, an important aspect is not sufficiently reflected; plausibility, in terms of being a subjective measure of likelihood, is conditional on some knowledge. The importance of accentuating the knowledge dimension is acknowledged by several proponents of plausibility. For example, Ramírez and Selin (2014) state that "The knowledge under consideration – subjected to plausibilistic and probabilistic judgments – is ethereal" (2014, p. 66), and they emphasize the need for "exploring the limits of available knowledge and sparking more effective inquiry" (2014, p. 66). Guimarães Pereira et al. (2007) highlight the importance of incorporating assessments on the knowledge supporting 'plausibility claims', i.e. statements about the future and how it may develop – particularly addressing the divides that exist between those producing the knowledge and those using it to support policy and decision-making. Yet, to the best of our knowledge, we cannot see that the practical application of plausibility is accompanied by approaches and methods for taking such issues into account. According to the plausibility-based approaches from the school of intuitive logics, "Storylines are usually developed through a group process in which the assumptions and mental models of the storyline writers remain unstated" (Alcamo, 2008, p. 142). Furthermore, these approaches are combined with the application of plausibility as a non-ordinal measure, since "By convention, Intuitive Logics scenarios are presented as equally plausible with no comment on their respective likelihoods" (Lloyd and Schweizer, 2014, p. 2054).

We argue that this practice gives rise to several challenges. A main purpose of assessing the likelihood of future events or outcomes is to inform and support decision-making. By offering a purely qualitative approach to likelihood assessment, plausibility is claimed to "open up decision making to language that can account for intuition, imagination and experience in a far richer and more meaningful fashion than the numbers can achieve" (Selin and Guimarães Pereira, 2013a, p. 103). However, as noted by Morgan and Keith (2008), "When scenarios are useful to decision makers, it is hard to avoid the conclusion that they are useful precisely because they communicate, in some measure, the analyst's judgment about the relative probability of various futures to decision makers" (2008, p. 196). Merely left with a range of equally plausible scenarios or outcomes, relevant stakeholders may not possess the necessary information to support decision-making. Moreover, according to Schneider (2001), the exclusion of relative likelihoods could lead to decision-makers and non-experts being "left to work out the implicit probability assignments for themselves" (2001, p. 18). Yet, when stakeholders are substituting their own judgments, they do so based on an understanding of plausibility that could potentially be very different from that of the scenario analysts. Notably, according to Walton et al. (2019), the majority of research related to the plausibility concept "emphasizes how researchers or developers of scenarios interpret plausibility rather than how stakeholders do. We see understanding the stakeholder perspective as a gap in knowledge" (2019, p. 44); thus, such a practice could result in "different 'cultures of plausibility' that may clash, especially between scientists' and policymakers' understandings of what constitutes a plausible future" (Schmidt-Scheele, 2020, p. 71).

Furthermore, as mentioned above, any subjective measure of likelihood is conditional on the background knowledge supporting the assignment. This knowledge, interpreted as 'justified beliefs' (Hansson, 2002; SRA, 2015) and founded on data, information, testing, models, argumentation, etc. (Aven, 2020), is often expressed as assumptions and could be more or less strong – or potentially erroneous. The concept of plausibility is put forward as a suitable measure of likelihood for situations with high complexity and uncertainty. It is argued that plausibility allows us to generate new knowledge and insights by "recognizing the part of uncertainty that is unpredictable and by actively exploring the sources of the turbulence and uncertainty" (Ramírez et al., 2017, p. 2). However, for complex systems, lack of knowledge is a main source of uncertainty, and, thus, the knowledge supporting plausibility judgments becomes an essential aspect of the assessment that also needs to be addressed. According to O'Mahony (2014), "Plausibility is determined by the analysis of the historical and current situation, potential evolution of driving forces discerned from the literature and comparison with existing forecasts" (2014, p. 46). The assumptions underlying such an analysis could be based on a weak foundation of knowledge, potentially giving rise to surprising events or outcomes relative to current beliefs. Assertedly, a key purpose of scenario approaches is to help "surface implicit assumptions, test tacit knowledge, question preconceptions of the impossible and the possible, change views and minds" (Ramírez and Selin, 2014, p. 66). Yet, in practical applications of plausibility as a measure of likelihood, such reflections are rarely included.

The knowledge dimension is, however, highlighted in the second category of interpretations identified in Section 2, which relate plausibility to the strength or quality of the background knowledge supporting the assessment. According to this perspective, plausibility does not represent a measure of likelihood per se but constitutes part of the foundation for likelihood assignments, by providing reflections on the underlying knowledge and assumptions that the judgments are based on. Considering assessments on the supporting knowledge an essential aspect of plausibility is a view held by several scholars, including Majone (1989, as cited in Schmidt-Scheele, 2020), who emphasizes the notion that "the credibility of a data's source as well as its scientific quality (validity, reliability) can play a significant role for assessing the overall plausibility of an argument" (2020, p. 89). Similarly, in the NUSAP system for assessing uncertainty, plausibility is associated with judgments on the strength or quality of the supporting knowledge. The NUSAP notational scheme consists of five qualifiers ('Numeral', 'Unit',

'Spread', 'Assessment', 'Pedigree'), of which the 'pedigree' qualifier aims to convey "an evaluative account of the production process of information, and [indicate] different aspects of the underpinning of the numbers and scientific status of the knowledge used" (Van der Sluijs et al., 2005, p. 482). This evaluation of the knowledge base is often facilitated using a so-called pedigree matrix, in which plausibility (interpreted as the degree to which an assumption is in accordance with 'reality') constitutes one of the assessment criteria (Van der Sluijs et al., 2005; Boone et al., 2010). Although some scholars assert that, by providing insights on the supporting knowledge, plausibility can be considered a complementary concept to likelihood measures (see e.g. Janasik, 2021; Tversky and Kahneman, 1973), notably, others claim that the reflections on supporting knowledge and data offered by plausibility serve as a substitute for probability in contexts where likelihoods cannot be meaningfully assigned. For example, Refsgaard et al. (2007) assert that "If probabilities cannot be quantified in any undisputed way, we often can still qualify the available body of evidence for the possibility of various outcomes in terms of plausibility or convincingness of the evidence" (2007, p. 1546).

The above discussion makes it clear that the plausibility concept relates to both likelihood, as a measure of uncertainty, and knowledge aspects that extend beyond likelihood. The knowledge aspects are made explicit in the interpretations belonging to category II, but the knowledge feature also comes into play in the interpretations from category I; by viewing plausibility as a subjective measure of likelihood, it follows that any plausibility assessment is conditional on the background knowledge that the judgments are based on. Yet, the knowledge dimension is not explicitly incorporated in the category I definitions of plausibility. Hence, the implication of embracing such a perspective (category I) on plausibility is that the background knowledge supporting the analysis often remains tacit. According to the category II interpretations, on the other hand, assessments of the supporting knowledge are the focal aspect of plausibility. However, the definitions belonging to this category do not provide any clear reference to likelihood; thus, it is not clear whether the concept of plausibility is to be seen as a complement to, or substitute for, uncertainty characterizations.

The analysis demonstrates that current interpretations of the plausibility concept capture both the likelihood and knowledge dimensions, but the relationship between these two dimensions is not clarified. In the coming section, we will suggest an interpretation of the plausibility concept which integrates these two dimensions in a logical way using risk science knowledge.

4. Improving the understanding and use of the plausibility concept based on prevailing risk science theory

For risk problems or issues characterized by large uncertainties, relying on a broad set of tools to reflect what we know and do not know about the future can be a fruitful approach for ensuring that risk is evaluated and expressed in a prudent manner (Dubois, 2010; Flage et al., 2014). As the present authors see it, plausibility brings some valuable ideas to the table in this regard, as the concept comprises two key aspects of risk: likelihood and knowledge. However, a stronger foundation of the plausibility concept is needed to make it scientifically sound and understandable for practical use. Current definitions of the concept and practice relate it to both likelihood and knowledge but without providing a convincing logic for combining these two aspects, as discussed in Section 3. In the following, we will show how contemporary risk science can help establish such a logic and offer a framework for how to understand and use the plausibility concept. Furthermore, we point to some of the implications these findings have for risk management and decision-making. A concrete risk assessment and decision-making context will be used to illustrate the discussion.

4.1. How should plausibility be understood in a risk context?

Plausibility is often referred to in relation to scenario analysis and future studies. However, the literature from these fields rarely includes reflections on how the concepts of plausibility and scenarios relate to risk. In the following, we use a general framework for conceptualizing risk to show how scenarios and plausibility are related to the main components of the risk concept: consequences and uncertainty, respectively.

The conceptual basis supporting the framework of risk adopted in the present paper is often referred to as an uncertainty-based risk perspective and follows the fundamental ideas as presented in documents by the Society for Risk Analysis (SRA, 2015; 2018). These sources also provide a foundation for the interpretation of key concepts addressed in the current paper, including probability, uncertainty and likelihood. According to this framework, risk is understood as the two-dimensional combination of i) the consequences (C) of an activity, with respect to something of human value, and ii) the uncertainties (U) associated with these consequences. Hence, we can write risk = (C,U). The consequence dimension is here interpreted in a broad sense, not only including outcomes but also covering aspects such as risk sources/risk influencing factors, events/hazards and the performance of barriers. Often the consequences are related to objectives, for example as the degree to which a goal or target level is met. To describe risk, C needs to be specified. This is done by identifying a set of consequences C' (e.g. risk sources, events/hazards, outcomes, etc.) to characterize C. Scenarios can be interpreted as a way of representing C', i.e. an approach for identifying and describing the potential consequences of an activity. Depending on the context, scenarios can be understood in different ways. According to Kaplan and Garrick (1981), a scenario refers to a sequence of events leading up to some undesired outcome. Based on this notion, scenarios are generated by questioning: "What can go wrong?". Which aspects of the consequences are reflected in the scenarios depend on the approach used to address this question. For example, in the approach presented in the Seveso III Directive on the control of major accident hazards, the accident scenarios cover aspects such as triggering events, external risk influencing factors and descriptions of protective and interventive barrier systems (European Parliament and Council, 2012). In frameworks related to scenario analysis and future studies, however, the scenario concept often takes on a broader meaning, representing long-term potential trajectories of future development based on a number of factors and driving forces, including macro-level aspects such as technological, political, environmental and socio-economic trends. The latter type of scenarios is often applied in contexts where the observed activity is of a broad type, e.g. the life in a country, the development of a technology or the management of natural resources. Another important distinction that should be mentioned is that the former interpretation of scenarios typically focuses specifically on undesired consequences, whereas the broader type of scenarios could also include outcomes that are positive/desirable. However, when referring to this type of scenario in a risk context, there will always be at least one scenario in the set of consequences where the outcome is considered negative.

The uncertainty component (U) represents the condition of incomplete knowledge, or lack of knowledge, about what the consequences (C) will be, and hence these two dimensions are closely intervened. Different tools can be used to express this uncertainty (the most common being probability), and the concept of plausibility enters the scene as one such tool. Thus, the juxtaposition of plausibility against concepts such as probability and possibility is essentially a comparison of different ways of expressing uncertainty. The notion of these concepts (probability, possibility, plausibility) as devices for measuring uncertainty is rarely stated explicitly in scenario analysis literature. However, when plausibility is referred to as "a vehicle for selecting scenarios and for presenting them as 'justified' assumptions about the future" (Schmidt-Scheele, 2020, p. 58), it is with reference to the concept representing a

qualitative assessment of the uncertainties related to some specified consequences (scenarios).

Having established a formal set-up linking scenarios and plausibility to the conceptual framework for risk, we can make some further reflections on what the plausibility concept expresses in a risk assessment and decision-making context. To illustrate the discussion, we consider an example related to the current coronavirus pandemic.

The outbreak of COVID-19 has led to devastating social, industrial, cultural and economic consequences worldwide, some of which have yet to be seen. The rapid development of vaccines and the implementation of mass vaccination campaigns has given global society an upper hand in the fight against the virus. Yet, an integral question remains: how will SARS-COV2 develop? In order to establish efficient strategies and practices to confront the virus, governments and health authorities need to know what to prepare for. The future trajectory of the pandemic depends on a number of factors, such as how vaccinations are distributed, willingness among individuals to be vaccinated, the virus' ability to mutate, the efficacy of vaccines against new variants of the virus, etc. (Saad-Roy et al., 2020; Telenti et al., 2021). Other important aspects that may influence the development, is the performance of emergency preparedness systems and mitigation strategies (Lindhout and Reniers, 2020). Based on these factors, analysts can specify a set of potential scenarios C' = {S_1, S_2, S_3} that could occur. One such scenario could be, for example, the eradication of the virus. Another scenario could be a seasonal resurgence of COVID-19. In such a setting, it is common to refer to these scenarios as plausible (Atkeson, 2020; Team and Hay, 2020). What does it mean, and is this use a meaningful and prudent way of characterizing risk?

To provide answers to these questions, it is clear that the scenarios alone do not provide the necessary information needed to support decision-making. The analysts need to include assessments on the uncertainty associated with the specified scenarios – and in particular how likely they are to occur. Allowing decision-makers to compare options and prioritize resources is a main purpose of the risk assessment, but it is difficult to see how this can be done unless some sort of consideration of uncertainties and likelihood is made. As any likelihood judgment is conditional on the knowledge of the assessors, the information presented to decision-makers needs to reflect this aspect by including considerations on the knowledge dimension: what is known, what is unknown, and how strong is the knowledge supporting the judgments? Based on this reasoning, a proper characterization of uncertainty should contain the following elements (Aven, 2017):

(1) A measure of uncertainty
(2) A judgment on the strength of knowledge supporting this measure
(3) The knowledge with its basis

In the current example, the analysts use plausibility to express the uncertainties, combining (1) and (2). To illustrate the idea, a matrix model can be used, see Fig. 1. Here, plausibility is represented by the two dimensions likelihood and knowledge, each assigned a value of 'low' and 'high'. All four quadrants are covered by the plausibility concept, yet the components constituting the concept can appear in different combinations, as shown in the model. Although the strength of knowledge is categorized from weak to strong, the notion of strong knowledge needs to be seen in relation to situations characterized by large uncertainties, as this is the type of context where plausibility is mainly used.

In situations with large uncertainties, plausibility offers an alternative qualitative approach to uncertainty assessment, combining the likelihood and knowledge dimensions. The concept allows for analysts to present a description of the risks and uncertainties associated with scenarios, without requiring them to make specific likelihood assignments that may not be justified. However, for the purpose of providing decision-making support, there are some limitations related to its use. In the following section, these limitations are further outlined, and the gained insights are used as a basis for discussing some important implications for risk management and decision-making.

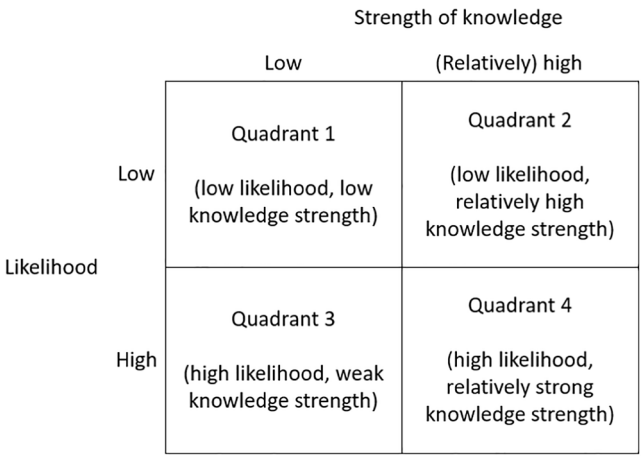

Fig. 1. Plausibility matrix.

4.2. Implications for risk management and decision-making

According to the set-up proposed in Section 4.1, knowledge constitutes an essential feature in the understanding and use of the plausibility concept. However, in order to understand the implications of such a perspective, some key aspects of knowledge need to be clarified. Of particular importance is the acknowledgement that knowledge is not static; it develops across time. The process of knowledge generation and development can be described in different ways. Peirce (1867), for example, describes this dynamics by referring to three stages of awareness; firstness, secondness and thirdness, each representing a stepping stone on the path between the unknown and the known. A similar notion is presented by Lindhout et al. (2020), who represent the development of knowledge as the movement between different domains on a so-called 'unknownness-scale'. Regardless of how the process of knowledge generation is characterized, a focal point is that knowledge is a dynamic concept. This acknowledgement not only opens up for the notion that "what would have been a surprise at one specific point in time would not necessarily be later, as the knowledge base can change" (Glette-Iversen and Aven, 2021), it also emphasizes the need for suitable approaches and methods that address potential gaps in the knowledge base.

It can be questioned to what extent the current use of plausibility allows for such considerations to be made. Firstly, the concept does not distinguish between the likelihood dimension (1) and the knowledge dimension (2). Hence, it is difficult to determine the contribution from each of these aspects. If scenario S_1 is assessed as more plausible than S_2, does that mean that the scenario is considered more likely or that the evidence/theory/knowledge supporting the assessment is considered stronger? Neither of these components is given an explicit value, making it difficult to use the information to make comparisons and prioritizations. Furthermore, it does not allow us to address the dynamicity of the supporting knowledge. Consider, again, the example related to the COVID-19 outbreak. Let us assume that scientists are able to develop more advanced epidemiological models, allowing them to predict, with a higher accuracy than previously, the future development of the pandemic. Hence, the strength of the knowledge supporting the assessment has changed (e.g., the scenario has moved from quadrant 1 to quadrant 2 in Fig. 1), yet the plausibility judgments for each scenario could remain the same, as there are still considerable uncertainties involved. When stating that a scenario is plausible, the likelihood is judged to be above zero, and this judgment of likelihood is supported by

some knowledge. But, how much above zero and how strong the knowledge needs to be, the statement does not reveal. However, if no precision is offered on the knowledge dimension, how can we capture changes in the knowledge, and how this affects the overall judgment of plausibility? Clearly, the formulation of the statement as plausible has a strong subjective basis, as there is no reference to the level of likelihood and strength of knowledge that is required. Without making specifications concerning the likelihood and knowledge dimensions, a precise and meaningful definition of the plausibility concept does not seem possible. But making such specifications is also problematic, as there are many ways of balancing likelihood and knowledge. And a main idea of the plausibility concept is to avoid being too precise on these dimensions, as the situation is characterized by large uncertainties.

Secondly, current practical applications of plausibility rarely include reflections concerning (3). If decision-makers cannot trace the information/knowledge supporting the assessment, important aspects of uncertainty could remain undisclosed. There could be events or scenarios that the current methods and approaches are unable to capture. Such events are often referred to as black swans; events that come as surprises relative to the present knowledge/beliefs (Taleb 2010; Aven 2013). Another term used is 'atypical scenarios' (Paltrinieri et al., 2013), representing scenarios that deviate from normal expectations of unwanted events or worst-case reference scenarios. Common characteristics for this category of scenarios is a "Lack of knowledge of analysts and methodologies [that are] unable to lead the analysts to the identification of atypical events". (Paltrinieri et al., 2013, p. 351). Scrutinizing the knowledge base supporting the assessment is an important tool for confronting this type of events; by challenging key assumptions, addressing the limitations of the models used and giving due attention to early signals and warnings, new knowledge can be obtained, potentially uncovering previously unknown events and scenarios. Considerations on the supporting knowledge are an essential aspect of risk management, giving weight to the acknowledgement that there is a leap between the results of the risk assessment and the decision-making that the assessment is meant to support. An important means of reducing this gap is conveying the risk and uncertainty description in a way that allows decision-makers to reflect on aspects that go beyond the presented risk and uncertainty judgments. For example, decision-makers need to take into account that the assessment is based on a number of assumptions, and that these could potentially be misleading or erroneous. This process, often referred to as managerial review and judgment, is of particular importance in contexts with large uncertainties, where the knowledge base supporting the assumptions is weak and, thus, the potential for experiencing surprising events/scenarios that were not considered in the risk assessment, is large.

Plausibility is considered a suitable approach for expressing uncertainty in contexts where the knowledge base is weak. The concept is based on the fundamental logic that large uncertainties imply an aversion towards making specific judgments on knowledge and likelihood. However, lack of knowledge constitutes an important part of the uncertainty dimension, and thus, the tools used to express uncertainty under such conditions need to open up for reflections on the limitations of and the strength of the supporting knowledge. As the situation is characterized by large uncertainties, the main purpose is not to assign exact probabilities as these could be difficult to justify. However, we may still provide some explicit reflections on the likelihood and knowledge dimensions by using imprecise probabilities, supported by judgments on the supporting strength of knowledge. Assessing the strength of knowledge often include reflections on issues such as reasonability of the assumptions made, the amount of reliable and relevant data/information, the degree of agreement among experts, phenomena understanding, the existence of accurate models and the degree to which the knowledge base has been scrutinized with respect to surprising events (Flage and Aven, 2009; Aven and Thekdi, 2021). A fundamental lack of knowledge would signify an essential contribution to the overall judgment of risk, and thus, such considerations can provide valuable information also in contexts where uncertainties are large.

In the above analysis, we have focused on probability and imprecise probability as measures of uncertainty. The argumentation also applies to Dempster-Shafer theory with its belief and plausibility functions. The theory provides an alternative measure of uncertainty but does not cover the elements (2) and (3). The evidence producing the belief and plausibility functions could be based on judgments by one rather poor expert, but this would not be revealed by these functions as they are transformations of the evidence available. The plausibility function from the Dempster-Shafer theory is thus not comparable to the plausibility concept discussed in this paper, which relates to both (1) and (2). Rather, we can see the plausibility function as an aspect of the uncertainty measure (1).

5. Conclusions

The concept of plausibility is often referred to in contexts with large uncertainties, but a clear interpretation of what the concept means in a risk context is missing. By reviewing current definitions and practical use of the concept, new insights are gained into what the concept is actually expressing. The analysis has shown that plausibility can be given an interpretation in a risk context by linking it to the likelihood and knowledge dimensions when describing risk. Based on this reasoning, plausibility can be understood as a measure of uncertainty, combining likelihood and supporting knowledge judgments.

It is, however, difficult to give a precise definition and meaning of the concept, without incorporating specific judgments of likelihood and knowledge. Yet, avoiding precision is an intrinsic idea of the plausibility concept, and the likelihood and knowledge dimensions are rarely addressed explicitly in practical applications of plausibility. This lack of precision introduces some challenges, particularly when it comes to the concept's ability to provide decision-making support and highlight important aspects of risk and uncertainty that could be concealed in the knowledge supporting the assessment. Fundamental issues in this respect, are the degrees to which the concept is able to reflect the knowledge dynamics and the potential for surprising events. Such issues are of particular relevance in situations with large uncertainties, where the knowledge base supporting the assessment is weak and the potential for experiencing surprises relative to this knowledge is large. Because plausibility is used in precisely these contexts, such reflections should constitute an integral aspect of the concept.

A main conclusion of the paper is that the use of the plausibility concept needs to be supplemented by judgments of imprecise probability and knowledge strength. That an event or scenario is plausible is a vague statement – a scientific approach would require some precision on both likelihood and knowledge.

CRediT authorship contribution statement

Ingrid Glette-Iversen: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Visualization. **Terje Aven:** Methodology, Supervision, Validation, Conceptualization, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Roger Flage:** Writing – original draft, Supervision, Conceptualization, Project administration.

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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