

# Ambiguity in Risk Assessment

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**Abstract:** This paper aims to shed light on the concept of ambiguity in engineering risk assessment. The objectives are to 1) Clarify the meaning of ambiguity in risk assessment; 2) Describe sources and manifestations of ambiguity in preassessment, risk analysis, and risk evaluation/decision-making; and 3) Outline a procedure for approaching ambiguity in practice. To address these objectives, we first review existing definitions of ambiguity, which are argued to be of limited relevance to engineering risk assessment. We then propose a new overall definition of ambiguity as a challenge in risk-informed decision-making, and define linguistic, contextual, and normative ambiguity as distinct categories of ambiguity that have different implications for risk assessment. Based on this, we list concrete sources and manifestations of ambiguity in risk assessment in a set of tables that can be used as a checklist for identifying ambiguity in the assessment process. We finally outline a stepwise procedure for approaching ambiguity in risk assessment, in order to provide practical guidance and stimulate further research on ambiguity in risk-informed decision-making.

**Keywords:** Ambiguity, Risk Assessment, Risk-Informed Decision-Making

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## 1. INTRODUCTION

Ambiguity permeates many strategic decisions that involve major accident risk. There might be ambiguity concerning the information needed to inform the decision-process, the basis for providing it, and its meaning and implication for decision-making. This can be traced back to ambiguity in the interpretation of *risk* [33], which is commonly defined as the answer to three questions: 1) What can happen? 2) How probable is it and/or how uncertain are we? and 3) If it does happen, what are the consequences? [2, 22]. *Risk assessment* can be defined as the process of defining, answering, and evaluating these questions in the phases of preassessment, risk analysis, and risk evaluation/decision-making. There are many sources and manifestations of ambiguity in this process, for example, concerning scope and boundary conditions, critical assumptions, and formulation of decision criteria [34]. Klinke and Renn [24] consider ambiguity as a defining challenge to risk assessment that calls for participatory approaches to risk-informed decision-making, such as the analytic-deliberative approach of NRC [27]. There is, however, limited guidance on how to identify and approach ambiguity in risk assessment by such approaches.

There are several alternative interpretations of ambiguity in the risk and decision-making literature. Some associate it with conflicting values and beliefs about *consequences* in the third question of risk [19, 34], others with incomplete knowledge in the assessment of *probabilities* and *uncertain events* in the first and second question of risk [6, 13], yet others with imperfections in human judgments [9, 25]. Many of the interpretations are problematic in light of foundational research on engineering risk assessment [2] and little has, to our knowledge, been done to scrutinize the concept of ambiguity in this context. In order to improve the role and value of risk assessment in risk-informed decision-making, there is a need for clarifying the meaning, sources, and manifestations of ambiguity in the different phases of risk assessment and to provide guidelines for approaching it in practice.

The purpose of this paper is to: 1) Clarify the meaning of ambiguity in risk assessment, 2) Describe sources and manifestations of ambiguity in the assessment process, and 3) Outline a procedure for ap-

proaching ambiguity in practice. The paper is delimited to engineering risk assessment for strategic decisions involving major accident risk. The paper is structured as follows: first, alternative conceptions of ambiguity in the literature are discussed in Section 2, before a new conceptualization is proposed in Section 3. Section 4 describes sources and manifestations of ambiguity in risk assessment, before a procedure for approaching ambiguity is presented in Section 5. Concluding remarks are given in Section 6.

## 2. LITERATURE ON AMBIGUITY

In this section we present and discuss common conceptions of the term *ambiguity* in everyday English language and in the risk literature. We argue that they are not sufficient for approaching ambiguity in risk assessment, before we present a new definition of ambiguity in the following section.

A dictionary definition of ambiguity is “a word or expression that can be understood in two or more possible ways” [26]. This conception is seen in some risk assessment applications, for example, Colyvan [10] explains ambiguity as “uncertainty arising from the fact that a word can be used in more than one way, and in a given context, it is not clear which way is being used.” The distinction between ambiguity and *vagueness* is stressed, where vagueness is something that is “stated in a way that is general and not specific” [26] and hence permits *borderline cases*. Vagueness is about the difficulty of making any interpretation, whereas ambiguity is about making several interpretations. Ambiguity is by this conception a linguistic property of statements that *can* be given multiple meanings depending on the context in which they are interpreted. This explanation is clear, but confined on the grounds that it concerns isolated statements and not how they appear in risk assessment.

A second conception of ambiguity is found in the literature on risk governance [3, 19, 24, 31]. Key to this interpretation is the existence of multiple values and perspectives on the severity, tolerability, and wider meanings of risk; manifested as disputes about framing, ethics, and trust. Ambiguity here corresponds to ambivalence and controversy and refers to the social situation around risk. The International Risk Governance Council [19] coins two types of ambiguity:

1. *Interpretative ambiguity* refers to different interpretations of identical assessment results and “factual” states of the world (e.g., whether an outcome is adverse or not), which is a result of people processing risk information according to their own risk constructs and images.
2. *Normative ambiguity* refers to different perspectives regarding the tolerability of the risk, which comes from differences in applying normative rules for evaluating the states of the world (e.g., fairness and distribution of risk and benefits).

Both are restricted to *consequences* that have an impact on something humans *value* [30]. Stirling [34] elaborates that “under conditions of ambiguity, it is not the probabilities but the possible outcomes themselves that are problematic,” and that ambiguity concerns “contradictory certainties” that cannot be objectively described by a single risk picture. While the inference is legitimate, the characterization is conceptually challenging as it implies that situations of ambiguity can be distinguished from situations where risk can indeed be objectively and uniquely described. This is in contrast to a broad line of risk research that acknowledge that risk is not an ontological property that can be objectively and unequivocally assessed [1, 2]. A second limitation is that the categories of interpretative and normative ambiguity are vague and intimately interrelated; one can be a source of the other and it is difficult to draw the line where one stops and the other begins. The prefix *interpretative* is in our view superfluous, and normative ambiguity extends beyond tolerability issues as a distinct source of (interpretative) ambiguity. Tolerability of risk furthermore depends on the other objectives in a decision problem and boils down to not knowing what alternative to choose, which is in our view something wider than ambiguity [15]. The greatest limitation is, however, that ambiguity is restricted to conflicting interpretations of risk

assessment results, thus failing to explain how it enters risk assessment in the first place.

A third conception is found within decision theory, statistics, and economics. This is a group of definitions that attribute ambiguity to the assessment of *uncertainties* and/or *probabilities*. Camerer and Weber [8] summarize five such conceptions, concerning *second order probability*, *quality of information*, *weight of evidence*, *source credibility*, or *unknown, but knowable information*. A common feature is that ambiguity is defined in relation to whether the true probability of an exhaustive set of outcomes can be known. Such interpretations are found in some risk assessment applications [5, 12], but are emptied of meaning if probability, like risk, is considered as a subjective construct in line with the arguments above. Another point of critique is that it is unclear how ambiguity differs from mere *uncertainty*, such as in the much cited definition of Ellsberg [13]: “a quality depending on the amount, type, reliability, and unanimity of information, given rise to one’s degree of confidence in an estimate of relative likelihoods of future events.” A special group of interpretations relate ambiguity to *impreciseness* in subjective expressions of uncertainty. This may either concern the informative basis for expressing uncertainty (e.g., we do not have sufficient information to specify whether our probability is 0.1 or 0.9) and/or vagueness in the description of uncertain events that permit borderline cases concerning their occurrence [6, 17]. Special approaches have developed to deal with such imprecision by non-probabilistic descriptions of uncertainty, for example, fuzzy logic or possibility theory [4, 10]. Some consider imprecision and vagueness as synonymous to ambiguity [21], whereas others stress that they are distinct concepts [10]. This group of interpretations is less controversial from an ontological point of view, but is in our view too limited because it ignores the consequence element in the definition of risk and fails to explain ambiguity as a defining challenge in risk assessment.

A final conception is found within behavioral research on individual and organizational decision-making. March [25] describes “ambiguities of choice” that go beyond the assessment of consequences and probabilities to human judgment and information processing in decision-making. March defines four types of ambiguities: Ambiguities of *preferences* (individual preferences may be vague, inconsistent, or unstable); ambiguities of *relevance* (the usefulness of information for decision-making may be unclear); ambiguities of *intelligence* (there may be several norms for what constitutes rational action); and ambiguities of *meaning* (lack of clarity regarding how one talks about the world and how meaning evolves from information). A study of ambiguity in safety cultures [32] describes the latter as lack of mutual understanding of words, symbols, and cultural manifestations in the process of creating and recreating meaning. Variants of March’s [25] conception is also found in risk assessment, for example, as “internal uncertainty” in decision-making that reflects imprecision in human judgments concerning preferences, values, and risk attitudes and may stem from insufficient understanding of problems, modeling assumptions, and so on [9]. Our main objection against these conceptualizations is that attributing ambiguity to limitations in human judgment instead of *what is being judged* circumvents the contextualities of risk and makes ambiguity a constraint rather than a defining challenge to risk assessment.

### 3. NEW DEFINITION AND CATEGORIZATION

The many conceptions of ambiguity are as such a source of ambiguity. Many of the interpretations are limited to one or two questions in the definition of risk, and are problematic by some risk perspectives. Few of the interpretations are broad, yet specific enough to guide the identification and treatment of ambiguity in risk assessment. A message of this paper is that there are several types of ambiguity that are distinct, yet closely related in the process of defining, answering, and evaluating the three questions of risk. In the following, we propose a new overall definition and clarify three categories of ambiguity that have different sources and manifestations in risk assessment.

### 3.1 An overall definition

We propose a new overall definition of ambiguity related to risk assessment:

**Ambiguity:** The existence of multiple interpretations concerning the basis, content, and implications of risk information.

By *risk information* we mean descriptions of risk in a broad sense; covering scenarios, probability distributions, risk metrics, uncertainty factors, sensitivities, and so on [2]. By *content* we refer to what these descriptions express, while we by *basis* refer to the information and judgments that underlie them. By *implications*, we mean how the information fits into and is evaluated in a decision context, but not what solution should be chosen. The ambiguity can be *intra-* and/or *inter-individual* in the sense that it may refer to multiple interpretations by a single individual (e.g., a decision-maker makes two alternative interpretations) or single interpretations by multiple individuals (e.g., a decision-maker makes one interpretation and a stakeholder makes another interpretation). The two are conceptually the same for a decision-maker who makes a decision on behalf of herself and relevant stakeholders. Inter-individual ambiguity may be evident, which may promote conflict and reduce confidence in risk assessment, but be sought resolved in the assessment. It may also go unnoticed until the assessment is finished, which may lead stakeholders to discard the risk analysis and oppose the decision after it is implemented.

The purpose of the overall definition is to clarify ambiguity as a defining challenge to risk assessment. In contrast to Klinke and Renn [24], who consider ambiguity as something that cannot be objectively assessed in distinction from something that is difficult, but possible to assess (i.e., complexity) or for which we lack sufficient scientific knowledge (i.e., uncertainty); we define it in multiple interpretations of risk information *conditioned* on limitations in the understanding of the system (i.e., complexity) and beliefs about what will happen in the future (i.e., uncertainty). Ambiguity is here a distinct challenge that hampers the use of risk assessment in risk-informed decision-making, and may amplify both uncertainty and complexity and influence the decision-maker's tolerability of both.

A key wording in the definition is “the *existence* of multiple interpretations”, which implies that ambiguity is not a potentiality as in the dictionary definitions, but a realization in the sense that multiple interpretations do exist (whether evident or not). If it was simply a potentiality, it would neither be defining nor of practical interest because it would be an omnipresent, conceptual challenge: it is first when multiple interpretations exist that the decision-maker has a problem. However, in order to approach ambiguity in risk assessment, it is necessary to also define it by its potential causes. We therefore define three categories of ambiguity in the following, which are potentialities that may or may not be realized as ambiguity according to the overall definition. The relation between the three categories and the overall definition in risk assessment is illustrated in a conceptual map in Figure 1. All categories may influence all the three phases of risk assessment, but have different implications and possibilities for resolution. The outputs of the three phases are the definition, answer, and evaluation of the three questions of risk, which may all be subject to (overall) ambiguity with respect to the basis, content, and implications of risk information.

### 3.2 Linguistic ambiguity

The first category is linguistic ambiguity, which mirrors the dictionary definition in Section 2:

**Linguistic ambiguity:** A statement that can be interpreted in two or more possible ways.

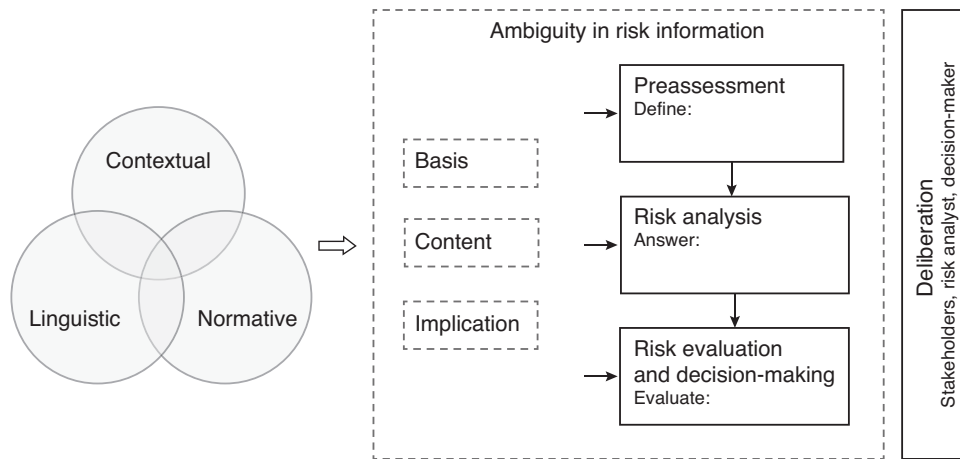


Figure 1: Conceptual map

The statement<sup>1</sup> may be written or oral, and can be a word or phrase, sentence, symbol, model, formula, parameter value, and so on. The statement,  $A$ , is formulated by a person (*addresser*), and interpreted by another person (*receiver*). The receiver assigns the statement an interpretation,  $B$ , in a process that is written  $A \rightsquigarrow B$ . A statement is *ambiguous* if it is, by reasonable logical deduction, possible to assign it two or more interpretations, i.e., both  $A \rightsquigarrow B_1$  and  $A \rightsquigarrow B_2$  (for  $B_1 \neq B_2$ ). Linguistic ambiguity is different from *vagueness*, which concerns *difficulty* in interpretation:  $A \rightsquigarrow ?$ . However, the practical distinction might be blurred as both concern unclarity in the communication of an intended interpretation (e.g.,  $A \rightsquigarrow B_1$ ) and are conditioned on the background knowledge of the receiver.

Linguistic ambiguity concerns the possibility that multiple interpretations can be deduced from a statement. It can therefore be seen as a property of statements that could, in principle, be measured by text analysis or intuitive evaluation. This could say something about the potentiality of a statement for giving rise to multiple interpretations, but not whether multiple interpretations are indeed made. Overall ambiguity as defined in Section 3.1 is a realization of this potentiality, which resides in the conjunction between the statement and its addressers and receivers. This concerns both what is being said and not said (“exformation”) and the different associations of the addressers and receivers [28], for example, because they have different professional or cultural background and experience.

The problem of linguistic ambiguity is captured in two “theorems” by Kaplan [21]:

*Theorem 1:* 50% of the problems in the world result from people using the same words with different meanings.

*Theorem 2:* The other 50% comes from people using different words with the same meaning.

Linguistic ambiguity implies that an interpretation may be right or wrong compared with the addresser’s intention, and thus promote inconsistencies and “wrong” judgments in risk assessment. Linguistic ambiguity can rarely be eliminated because of the inherent ambiguities of language and the impossibility of complete specification [28]. It is, however, possible to reduce it by being vigilant in both the formulation and interpretation of statements in risk assessment. Addressers should delimit the potentiality of multiple interpretations and receivers should be aware of this potentiality. A common strategy for reducing linguistic ambiguity is to standardize definitions of terms and variables by using standards such as [20]. Such standards may, however, be conflicting or of poor quality, and increase linguistic ambiguity in a

<sup>1</sup>Ambiguity concerns something that conveys *meaning* in the sense of being perceived, processed, or described by humans. It can therefore be attributed to representations or judgments about the objects under analysis, but not the objects themselves.

specific context. According to Rasmussen [29], any attempt of objective definition must be circular on the grounds that the properties of a statement depends on the context in which it is used. This relates to a different type of ambiguity that is not attributed to individual statements, but the context in which they are used to provide risk information.

### 3.3 Contextual ambiguity

The second category is contextual ambiguity, which we define as:

**Contextual ambiguity:** The existence of multiple contextualizations, premises, and knowledge relations in risk information.

This type of ambiguity does not concern multiple interpretations of a statement, but of the context in which it is used and derived. We are broadening the scope from a statement  $A$  with its alternative interpretations  $B_i$  ( $A \rightsquigarrow B_i$ ), for  $i = 1, 2, \dots$ , to alternative statements  $A_j$  with their respective interpretations ( $A_j \rightsquigarrow B_k$ ). The issue is not whether  $A_j$  or  $B_k$  are right or wrong; but that there can be multiple legitimate statements and interpretations. This is a more profound category of ambiguity that cannot be deduced from isolated statements, but the premises for which they are used in creating risk information. Contextual ambiguity is essentially about multiple knowledge relations and descriptions of risk [7].

Contextual ambiguity reflects the recognition that risk assessment produces contextualized knowledge that cannot be judged in relation to traditional scientific notions of objectivity and truth. According to Funtowicz and Ravetz [16], quality is a contextual, rather than universal property of risk assessment, and there is no single privileged point of view for measurement, analysis, and evaluation of risk information. Contextual ambiguity prevails when different framings and approaches to risk assessment provide conflicting risk information [35]. According to Slovic [33], this boils down to ambiguity in the definition of risk, since “there are no right or wrong definitions of risk, just different ones.” Ambiguities in the *social* definition of risk (i.e., by decision-makers and stakeholders) imply multiple perspectives on the purpose, scope, and boundaries of the risk analysis, whereas ambiguities in the *technical* definition (i.e., by analysts and researchers) imply multiple perspectives on its validity and approach.

Contextual ambiguity is distinct from, but may be amplified by *context dependence* [10], which is uncertainty arising from the failure to specify the context in which a word or statement is used, recognizing that any statement can assume a multitude of meanings in different contexts [18]. It is also related to IRGC’s interpretative ambiguity [19], but goes further in considering multiplicity in the basis and content of risk information and not only in the interpretation of identical risk assessment results.

Unlike linguistic ambiguity, contextual ambiguity cannot be implied from isolated statements, and it is not obvious whether it can be measured. Contextual ambiguity is also a potential in the sense that all risk assessments can be framed in alternative ways, but it is primarily a challenge if recognized in the assessment. A great distinction is that contextual ambiguity should not necessarily be reduced; it may even be desirable as it provides multiple perspectives on the decision problem [35]. Constructive utilization of contextual ambiguity presupposes, however, that both the sources and manifestations of contextual ambiguity are clarified in the assessment, and that discrepancies between the premises and approaches to risk assessment are identified throughout the process. What should be reduced is thus not necessarily the contextual ambiguity, but discrepancy in the creation of meaning within each context.

Social and scientific views are interwoven in the framing and creation of meaning in risk assessment [18], and contextual ambiguity is hence a compound issue that is determined by both scientific/analytical and social factors. To emphasize this connection, but make it possible to untangle it in risk assessment, we distinguish between contextual ambiguity, which concerns multiple knowledge claims, and normative

ambiguity as defined below, which concerns multiple value claims.

### 3.4 Normative ambiguity

The third category is normative ambiguity, which we define as:

**Normative ambiguity:** The existence of multiple, conflicting, and/or inconsistent values and norms in risk assessment.

This definition is related to, but different from IRGC's [19] conception of normative ambiguity. Our focus is on values and norms that govern the *entire* risk assessment process from preassessment to risk evaluation, but *not* the tolerability of risk as a balance between risk and other values (objectives) in decision-making, which is outside the scope of this paper. Normative ambiguity concerns the normative frame of reference for creating and interpreting risk information. It resides in the convictions of the addressers and receivers that formulate and interpret a statement, rather than the statement as such. It can therefore not be meaningfully explained by the statements  $A_n$  and  $B_n$ . Normative ambiguity can be seen as a special variant of contextual ambiguity related to *value judgments* in risk assessment.

Risk assessment is influenced by both scientific (e.g., validity, consistency, and explanatory power) and social values (e.g., moral intuitions, ethical principles, responsibilities, or political motives concerning safety, ecology, economy, and so on) [35, 36]. The social values are the objectives that drive decision-making and risk assessment [23], and are evident in the definition and evaluation of consequences in terms of values to be protected and trade-offs to be made. However, our conception of normative ambiguity permeates the entire risk assessment process through value judgments at each phase; from problem structuring and choice of risk metrics to analysis and treatment of uncertainties and sensitivities [11, 33]. It may also be entangled with and amplified by linguistic and contextual ambiguity, such that value conflicts are disguised as conflicts in the interpretation and quality of "factual" statements (i.e., as in IRGC's conception of interpretative ambiguity).

Normative ambiguity is challenging from a risk assessment perspective on the grounds that it implies difficult value judgments and trade-offs. Because of the "inherent ambiguity and value-loaded nature of risk" [18] and because different stakeholders (e.g., operating companies and authorities) inevitably will have different objectives and perspectives, it can rarely be eliminated [35]. It is, however, possible to reduce the potential for normative ambiguity by making value judgments explicit and consistent in the integration between analysis and deliberation, and in particular, to distinguish normative from linguistic and contextual ambiguity.

## 4. SOURCES AND MANIFESTATIONS OF AMBIGUITY IN RISK ASSESSMENT

In this section we point to concrete *sources* and *manifestations* of the different types of ambiguity in risk assessment. The sources and manifestations are derived from a wide literature (e.g., [14, 27, 30, 34]) and are presented in Tables 1-3, which correspond to the three phases of risk assessment. The main purpose of the tables is to create awareness of ambiguity in risk assessment, but they can also provide practical guidance as checklists for identifying and resolving ambiguity in the integration of analysis and deliberation as outlined in the following section.

The terms "sources" and "manifestations" are blended on the grounds that it may be difficult to tell whether an ambiguity represents a fundamental point of discern or results from earlier ambiguities. This invites challenging questions about the origin and propagation of ambiguity in risk assessment. Is it, for example, possible to say that a statement  $C$  that is derived from an ambiguous statement  $A$  ( $A \rightsquigarrow B_1 \rightsquigarrow$

Table 1: Preassessment

<i>Task</i>	<i>Source/manifestation of ambiguity concerning:</i>	<i>Type</i>
Definition of purpose	Mandate of risk assessment for informing decision-making. Objectives of decision problem with respect to risk (qualitative and quantitative).	C, N
Definition of scope and boundary conditions	Temporal, spatial, and organizational boundaries. External influences and environmental conditions. Desired resolution and precision.	L, C
Definition of central terms	Hazards, hazardous events, consequences, barriers, populations, etc.	L, C
Specification of information needs	Choice of risk metrics and presentation format. Qualitative information needs, e.g., for emergency preparedness and design.	C, N
Collection of background information	Interpretation and relevance of system drawings, references systems, experience data, expert judgments, plans and developments, stakeholder knowledge, etc.	L, C
Identification of stakeholder concerns	Objectives and concerns related to hazards, scenarios, etc.	L, C, N
Identification of constraints and challenges	Understanding of uncertainty and complexity as premises and/or limitations, identification of uncertainty factors and critical assumptions.	L, C
Choice of approach to risk analysis	Relevance, criticality, and fit between risk analysis methods and challenges. Understanding and interpretation of causality, uncertainty, complexity, etc.	C
Choice of approach to risk evaluation/decision-making	Relevance of decision-principles in light of identified constraints and challenges. Principles for integrating analysis and deliberation in decision-making.	C, N
Planning of risk analysis	Required time and resources, e.g., inclusion of disciplinary expertise.	C
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<i>Definition of the three questions of risk</i>	<i>Ambiguity in the basis of risk information</i>	
What can happen?	Scope for identification and analysis of hazardous events, scenarios, and causal influences	
How probable is it/how uncertain are we?	Understanding of probability and uncertainty as a premise and/or limitation, and required methods of treatment	
What are the consequences?	Scope for specification of endpoints, consequence dimensions, outcomes, and affected populations	

C) is ambiguous even if it is (linguistically) unambiguous? Our answer is that it must necessarily be so because of the web of potential interpretations that are discarded at an earlier stage (e.g.,  $B_2 \rightsquigarrow C_2$ ). The sources and manifestations may propagate throughout the risk assessment as a compound mix of linguistic (L), contextual (C), and normative (N) ambiguity, and considering statements in isolation is thus somewhat meaningless. A related challenge is whether it is possible to measure the relative criticality of the different sources and manifestations. Our answer is that on their own, they remain potentialities: what we are ultimately interested in is how the sources and manifestations lead to overall ambiguity in the basis, content, and implications of risk information through how the three questions of risk are defined, answered, and evaluated. We have therefore summarized the main manifestations of ambiguity in relation to the three questions of risk at the end of each table.

## 5. A STEPWISE PROCEDURE

In this section we outline a stepwise procedure for approaching ambiguity in risk assessment. The procedure builds on the previous sections and is extended to consider the use of risk assessment in risk-informed decision-making. The procedure is very coarse and is intended to serve as a point of departure for further research on how to approach ambiguity in risk assessment.

### 1. Identify sources and/or manifestations of ambiguity during each phase:

- Use table as a checklist



Table 2: Risk analysis

<i>Task</i>	<i>Source/manifestation of ambiguity concerning:</i>	<i>Type</i>
Detailed planning of risk analysis	Translation of specifications from preassessment into detailed definition of scope, boundary conditions, methodology, etc.	L, C
Acquiring and combining information	System observations (direct, written, or oral), system drawings, mock-up models, operational plans, reliability data, expert judgments.	L, C
Hazard identification	Guidewords and process parameters (e.g., in HAZOP), system drawings, mock-up models, etc. Screening criteria for hazards and scenarios.	L, C
Causal analysis	Accident models and principles for searching for causes and events. Definition of basic and TOP events and system states. Applicability of generic frequency and reliability data and need for adjustment, e.g., by organizational factors.	L, C
Consequence analysis	Definition of initiating events, barrier functions, and endpoints (cut-off limits). Definition of credible and worst case conditions and scenarios. Definition of exposures, affected populations, vulnerability and susceptibility models and thresholds.	L, C, N
Calculation of risk metrics	Averaging/aggregation over affected populations, implicit aversion factors and relative weights, discounting future consequences, translation of consequences into monetary value.	C, N
Documentation of critical assumptions	Operational and environmental conditions, e.g., response and duration times, weather conditions, etc.	L, C
Identification of limitations	Documentation of delimitations, simplifications, and approximations.	L, C
Uncertainty analysis	Treatment and presentation by point estimates, distribution, imprecise probabilities, etc. Description of qualitative uncertainty factors and possibility of surprise.	L, C
Sensitivity analysis	Impact and criticality of sensitivities with respect to uncertainty and/or confidence in the results, and their relation to basic premises and assumptions in the analysis.	C
Presentation of results	Multiple and conflicting presentation formats (e.g., numerical ranges and evaluative labels). Tacit assumptions between intermediate and final results.	C, N
Identification of risk reducing measures	Reduction in consequences and/or probabilities within and across hazards and scenarios.	L, N
Third party review and quality assurance	Reference standards for judging the quality of risk analysis.	C, N
<i>Answer to the three questions of risk</i>	<i>Ambiguity in the basis and content of risk information</i>	
What can happen?	Specification of hazardous events and accident scenarios. Scenarios that are knowingly or unknowingly left out of the analysis ("Black swans").	
How probable is it/how uncertain are we?	Quantitative, qualitative, and graphical descriptions of probability, frequency, and uncertainty	
What are the consequences?	Categories and descriptions of consequences for affected populations; risk metrics for intermediate and final endpoints	

## 2. Distinguish types of ambiguity

- Trace sources
- Identify and untangle compound manifestations

## 3. Resolve different types of ambiguities

- Linguistic: Specify. Seek reduction by showing vigilance in the formulation and interpretation of statements
- Contextual: Clarify. Seek congruence by eliminating discrepancies between the premises and approaches to risk assessment
- Normative: Make explicit. Seek consistency by exploring value judgments and preferences

## 4. In each phase, describe overall ambiguity in relation to the three questions of risk.

Table 3: Risk evaluation and decision-making

<i>Task</i>	<i>Source/manifestation of ambiguity concerning:</i>	<i>Type</i>
Managerial review of risk analysis report	Relevance of premises and assumptions. Criticality of related sensitivities and uncertainty factors.	L, C
Evaluation of confidence in risk analysis	Understanding and tolerability of uncertainty, complexity, and/or ambiguity in risk analysis.	C, N
Comparison of different types of analyses	Discrepancies between terms and contextual premises across analyses.	L, C, N
Balancing preferences and trade-offs	Inconsistency with objectives and concerns defined in preassessment (e.g., labile preferences). Double-counting of confidence-related aspects (e.g., uncertainty).	N
Evaluation of risk reducing measures	Definition, valuation, and distribution of costs and benefits, e.g., in time and across stakeholders.	N
Formulation of decision criteria	Basis and rationale for decision criteria, e.g., values of risk acceptance criteria, disproportionality factors, and discount rates in ALARP. Conditions for invoking the precautionary principle.	L, C, N
Comparison with decision criteria	Adjustment to account for uncertainty (e.g., safety margins); multiple presentation formats and/or criteria.	C, N
<i>Evaluation of the three questions of risk</i>		
What can happen?	Generalizability and completeness of scenarios. Relevance with respect to design and operation.	
How probable is it/how uncertain are we?	Interpretation of probability and uncertainty as a premise and/or limitation with respect to confidence in the results and comparison with evaluation criteria.	
What are the consequences?	Applicability of risk metrics as attributes in decision-making. Relevance of consequence categories to specific persons or objects.	

- Describe how the sources and manifestations of ambiguity lead to multiple interpretations of the basis, content, and implication of risk information.
- Give a coarse evaluation of the resulting ambiguity as *high/medium/low* and indicate whether it is mainly linguistic, contextual, or normative

5. Reconsider the approach to risk-informed decision-making in light of unresolved ambiguity, e.g:

- If ambiguity is high and mainly linguistic: the risk assessment should be iterated from the critical phase and be rewritten in deliberation with decision-makers and stakeholders, but can then provide the basis for managerial review and decision by a responsible decision-maker.
- If ambiguity is high and mainly contextual: managerial review and decision should be made in deliberation with relevant stakeholders and experts, comparing alternative risk descriptions with alternative evaluation criteria in light of the decision context.
- If ambiguity is high and mainly normative: consider deliberative principles for decision-making, using risk analysis as vehicle for discussions on preferences and tradeoffs.

## 6. CONCLUSIONS

The aim of this paper is to shed light on the concept of ambiguity in risk assessment. Ambiguity is in our view an important challenge that has not been fully recognized and explored in risk assessment; neither from a theoretical nor practical point of view. We have reviewed existing definitions of ambiguity and argued that they are too limited or conceptually problematic to be of use in engineering risk assessment. The theoretical contribution of the paper is a new overall definition of ambiguity as a distinct challenge that compromises the role and value of risk assessment in risk-informed decision-making. We have also defined linguistic, contextual, and normative ambiguity as three categories of ambiguity that must

be differently approached in risk assessment. The practical contribution of the paper is a set of tables that point to specific sources and manifestations of these categories in preassessment, risk analysis, and risk evaluation/decision-making. The tables also clarify the main implications of ambiguity in relation to how the three questions of risk are defined, answered, and evaluated in the respective phases. The main purpose of the tables is to create awareness of the many sources and manifestations of ambiguity in risk assessment, but they can also be used as a checklist for identifying and discussing ambiguity in an analytic-deliberative process. To assist in such a process, we have finally outlined a stepwise procedure for approaching ambiguity in risk assessment. The procedure is admittedly coarse and is intended to serve as a point of departure for further research on ambiguity in risk-informed decision-making. We have touched upon several challenging issues and have raised questions that have only been partly answered, for example, regarding the ontology, measurability, and propagation of ambiguity in risk assessment. By doing so, we aim to stimulate further work and discussion on ambiguity, and create awareness of an intriguing challenge that has yet to be fully recognized in risk assessment.

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