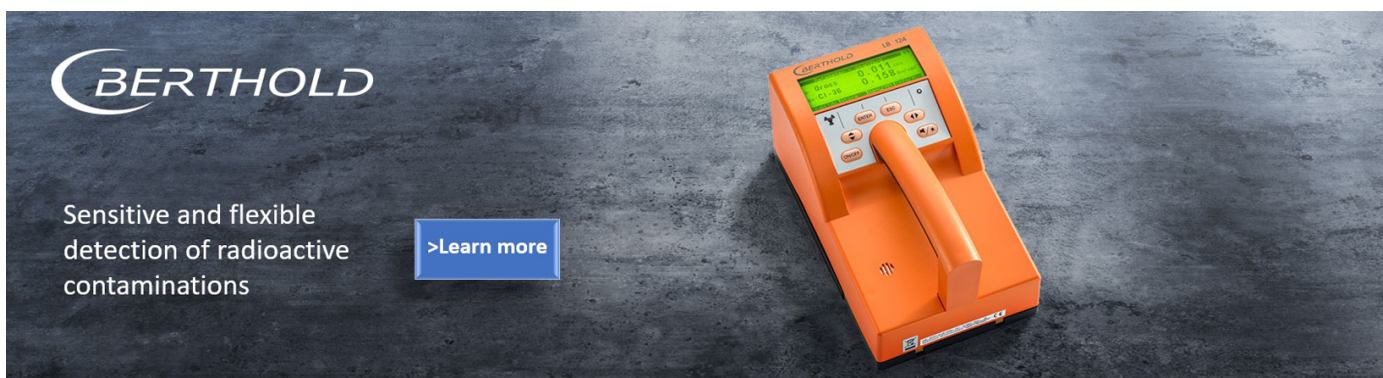


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Radiation risks and uncertainties: a scoping review to support communication and informed decision-making

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Abstract

Although radiation protection is challenged by many uncertainties, there is no systematic study investigating the definitions and types of these uncertainties. To address this gap, in this paper we offer a scoping review to comprehensively analyse, for the first time, peer-reviewed scientific articles ($n = 33$) related to uncertainties in the following radiation exposure situations: nuclear emergencies, decommissioning of nuclear/radiological installations and long-term radiological exposure situations (e.g. naturally occurring radioactive materials). The results suggest that *firstly*, there is no agreement regarding definitions of uncertainty, which is mainly defined based on its sources, types or categories rather than by its meaning. *Secondly*, different actors are faced with different types of uncertainties. Uncertainties of the scientific community are mostly data and methodology-driven (e.g. dose-response relationships), those of the decision-makers are related to the likely consequences of decision options and public reactions, while laypeople's uncertainties are mainly related to the trustworthiness of experts or the emotional potential of specific risk exposures. Furthermore, the majority of articles focus on the uncertainties of the scientific community, while those of the information receivers (i.e. decision-makers and laypeople) receive much less consideration. *Finally*, there was no

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difference in types of uncertainties across the different risk-related study areas analysed (radiation versus other risks). Based on these findings, we provide some preliminary recommendations regarding research on uncertainty related to radiation protection, as well as communication practices.

Keywords: uncertainty, radiation risks, communication, decision-making

Supplementary material for this article is available [online](#)

1. Uncertainties in radiation protection

The field of radiation¹ protection is challenged by associated scientific, technical and societal uncertainties related to ionising radiation. In the last decade, more attention has been paid to different aspects such as uncertainty evaluation and expression in dose and risk assessment (Allisy-Roberts and Day 2008). However, a gap still remains in uncertainties related to different applications, as well as understanding and evaluating the risks of ionising radiation in specific and radiation protection in general. For instance, uncertainties linked to exposure assessment may be related to the physicochemical behaviour and transport of radionuclides, transfer to biota, dosimetry and dose assessment in humans and biota (Hinton *et al* 2013). Another uncertainty concerns the possible relationship between background irradiation and cancer occurrence, particularly in children as they are substantially more sensitive to radiation exposure than adults (Wakeford *et al* 2009, UNSCEAR 2013, 2017, Hoeschen 2018). Moreover, assessment of occupational exposure from incorporated radionuclides is still subject to major uncertainties, due to activity measurement errors, individual variability, limited biokinetic and dosimetric models and unknown parameters of exposure (Boice 2010, Kreuzer *et al* 2018). It is also recognised that nuclear or radiological emergency response and recovery requires decisions under high uncertainty (Schneider *et al* 2017). Existing research argues that these uncertainties need to be communicated (Allisy-Roberts and Day 2008, Renn 2008b, Fischhoff and Davis 2014, Osman *et al* 2019) in order to empower laypeople (patients, workers, exposed population ...) as well as decision-makers to take informed decisions considering the risks and benefits of exposures to ionising radiation. This requires a good understanding of laypeople's and decision-makers' sense-making of ionising radiation concepts and related uncertainties (Christofides *et al* 2010).

According to the recent 'Strategic research agenda for social sciences and humanities in radiological protection' (Perko *et al* 2019), it is important that we capture different understandings of uncertainties related to radiation risks in order to bridge the gap between different concepts of uncertainty across various actors and research fields. To address the complexity of assessing causal and temporal relationships as well as sources of uncertainty related to radiation protection, existing research suggests that an analysis of the state-of-the-art knowledge is needed (Perko *et al* 2019). This would help in identifying and prioritising critical uncertainties, which is essential to decision-making (Van Asselt and Rotmans 2002, Walker *et al* 2003) related to radiation protection.

¹ Following the comments of the anonymous reviewers, the word 'radiological' has been replaced with 'radiation' as the former represents a more ambiguous term given that it is used also for a medical speciality and diagnostic imaging. The latter, on the other hand is more general and less ambiguous.

After acknowledging the relevance of uncertainty communication, numerous studies have been conducted regarding uncertainty and its related aspects, such as uncertainty analysis, classification, communication and decision-making under uncertain situations (Walker *et al* 2003, Maxim and van der Sluijs 2007, Beck *et al* 2016, Knoblauch *et al* 2018). These studies are present in different publications, are from different study fields, take into account the uncertainties of different actors and deal with different aspects of uncertainty. However, in the radiation protection field, there is no systematic study investigating the definitions and types of uncertainties. To address this gap, we conducted a scoping review to systematically analyse, for the first time, the uncertainties related to the following radiation exposure situations: nuclear emergencies, decommissioning of nuclear/radiological installations and long-term radiological exposure situations (e.g. NORM). For the purpose of this study, we preferred to focus on these three cases, since they represent core concerns of the European Commission (H2020 projects) and are less covered by scientific scrutiny than, for example, routine emissions from power plants. For instance, related to nuclear emergencies, many gaps and issues have been identified (especially after the Chernobyl and Fukushima accidents) that need to be addressed. Such issues involve creating and advancing different modelling and monitoring techniques; dealing with contaminated goods; improving decision support systems; issuing reliable and trustworthy information to the public in due time; as well as analyzing the public's perceptions of risks and uncertainties (Raskob 2017, Schneider *et al* 2017). Similarly, the TERRITORIES project under H2020 (Guillevic *et al* 2018) has clearly argued that more scientific attention needs to be paid to the impact of uncertainty on decision-making regarding long-term radiological exposure situations (e.g. NORM). Likewise, decommissioning of nuclear/radiological installations is also associated with many challenges and uncertainties which, if unaddressed, may result in unacceptable health, safety and security risks to the general public and to workers and increased risks to the environment (IAEA 2016).

By analysing the uncertainties present in the literature that treats different actors as respondents, we will be able to see the different uncertainties that these actors are faced with, thereby making it easier to realise what kind of information needs to be communicated to reduce uncertainties and allow information receivers to make informed decisions in radiation exposure situations.

In the next sections, we provide more precise clarifications of the concepts used in this scoping review as well as a theoretical background for the methods and analysis conducted. Afterwards, we present, interpret and discuss the results, and finally we conclude the paper by pointing out the main results and limitations of the study as well as recommendations for the radiation protection community.

2. Theoretical and conceptual background

There is extensive literature on risk perception, communication and governance in general (Fischhoff 2012, Renn 2008b; Slovic *et al* 2004; Slovic 1993), mainly arguing that investigating risk and uncertainty perception provides relevant background information for designing effective communication, structuring public discourse, informing judgments about risk acceptability and affecting public policymaking (Renn 2012). However, the literature related to communication of- and decision-making under uncertainties in the radiation protection field remains scarce and scattered.

The theoretical and conceptual background of this scoping review is based on the context of uncertainty communication and/or decision-making under uncertain situations. Following

(Harris 2015), we define *uncertainty communication* as a process of communicating uncertain information a) between actors in the scientific community, b) from the scientific community towards other actors such as decision-makers, media and laypeople or c) bottom-up uncertainty communication, namely from laypeople towards decision-makers or scientists. On the other hand, we define *decision-making under uncertainty* as a process of choosing from amongst several options for taking action (including doing nothing), in situations where there is contradictory, ambiguous, imprecise or no information at all (Renn 2008a). One of the main rationales of effectively communicating uncertainty is to help the receivers of the information make informed judgments and decisions to achieve the long- as well as short-term goals (Patt and Weber 2014). In contrast, failure in communication results in a lack of public trust in scientists, who seem not to know the needs of laypeople, and scientists' trust in the public, who seem unable to understand uncertain information (Fischhoff 2012). The same was argued to apply to authorities using science to base their decision-making and communication on (Perko 2016). For this reason, it is deemed relevant to focus on these two aspects of uncertainty and the linkage between them while reviewing the literature to answer our main research question, namely *what are the existing definitions and types of uncertainties in radiation risk literature (RQ1)?*

The classifications of uncertainty published in the literature are numerous and diverse (Maxim and van der Sluijs 2011). Yet, different authors argue that in the process of uncertainty communication, an important aspect is neglected, namely, the differences in types of uncertainty across different actors (Maxim et al 2013, Morris-Suzuki 2014). Although aiming to contribute to informed decision-making (Doyle et al 2014), communicating scientific uncertainties does not necessarily satisfy or decrease the uncertainties of laypeople. As (Maxim et al 2013) argue, laypeople raise different and more uncertainties than those of the scientists. Furthermore, not all uncertainties—especially uncertainty due to low-dose radiation risks, behavioural and societal variability, value diversity, technological surprise, ignorance and indeterminacy—can be adequately addressed with existing methods and tools (van Asselt and Rotmans, 2002). Similarly, (Walker et al 2010) argue that it is important to distinguish between what can be called the scientists' view of uncertainty and the decisionmakers'/policymakers' view of uncertainty. The existing typologies of uncertainty mainly focus on the perspective of the 'producer' of uncertainty information, thereby assuming that the message about uncertainty does not change when it is communicated between the producer (e.g. the scientist/modeller) and the information receiver (e.g. the decision-maker or laypeople) (Maxim and van der Sluijs 2011). For this reason, uncertainty is usually treated as a 'marginal issue, as an additional physical variable, as a mathematical artifact' (van Asselt and Rotmans 2002: 82). In any communication process, the messages produced and received are not identical. Ignoring this impacts the ultimate success of uncertainty communication (Maxim and van der Sluijs 2011) and poses serious problems for the scientists when delivering forecasts to the public through the press (Harris 2015). Furthermore, (van Asselt 2005) takes into account the fact that uncertainty is a social construction, thereby naming the 'constructors' as 'artists' which shape and reshape the concept of uncertainty. 'If we want to understand the uncertainty challenge' she argues, 'we have to take the artists into account as well' (van Asselt 2005). Based on these arguments, in this research, we will analyse *whether there are different types of uncertainties across different actors present in the literature review (RQ 1.1)* as a first sub-question of this research.

Following (Harris 2015), we divide the main actors present in the literature regarding uncertainty from a communication-and-decision-making-centred point of view into three groups: (1) *scientific community*—involving academia, scientific experts, observatories and other actors dealing with information and advice; (2) *decision-makers*—involving governmental bodies,

policymakers, regulators, enforcers, emergency actors, etc; and (3) *laypeople and other actors*—involving citizens, media, non-governmental organisations and the like (Harris 2015). It is important to state that this is not simply an issue of ‘scientists versus non-scientists’. It is more of an epistemological issue (Morris-Suzuki 2014), therefore, depending on the situation and issue at hand, even a member of the scientific community can be considered as a layperson in a particular case. In the case of the Fukushima disaster, there were uncertainties and criticisms towards the application of science in the disaster response, even between the scientists themselves (Morris-Suzuki 2014). This will be carefully taken into account when analysing the position and stakes of the actors while identifying the types and definitions of uncertainty.

In spite of the differences in uncertainties across different actors, scholars argue that epistemological differences amongst different study areas have contributed even more to the difficulty in finding a consensus regarding uncertainty. Additionally, different articles use different names for the same thing, or the opposite (the same name for different things) when talking about uncertainty (Romao and Pauperio 2016). The various existing uncertainty definitions and typologies hinder clear communication and, consequently, the understanding of existing uncertainties in the field of natural hazards according to (Kunz *et al* 2011). These arguments lead to the formulation of the second sub-question of this paper, respectively: *do uncertainty definitions and types in the radiation risk research literature differ from the definitions and types in other risk-related study areas (RQ 1.2)?* This way, we can see whether we can make generalisations when we talk about uncertainty across different fields.

The goal of this scoping review is, hence, three-fold: first, it will inductively review and summarise the existing definitions of uncertainties by focusing on the different terms, concepts, and types used to define it. Second, the focus will shift towards the types of uncertainties that are present amongst various actors (i.e. scientific community; decision-makers; and laypeople) in the literature. Third, we will analyse whether there are differences in definitions and types of uncertainty between radiation risk research and other study areas. Conclusively, the findings of this scoping review will be placed into the deeper context of what they mean for communication of uncertainties and decision-making in the radiation field.

3. Search method and analysis

In this paper we employed a scoping review as a method following the guidance from Joanna Briggs Methods Manual for Scoping Reviews (The Joanna Briggs Institute 2015). This type of literature review proved to be the most suitable given that the aim of this paper is to map and bring together the existing literature present in different study areas evolving around a broader research question with scattered evidence (Tricco *et al* 2016). A review protocol with basic planning and expectations was created internally, but not registered or made public. As a part of comprehensively reviewing the body of the literature, we use the ‘PRISMA extension for scoping reviews’ checklist (Tricco *et al* 2018) for the collection, analysis and reporting of this review.

Articles for the scoping review were collected in December 2018 using two search engines: Web of Science and Scopus. Web of Science covers a range of published articles from the year 1972, while Scopus covers articles starting from 1960. The combination of keywords was decided based on the three research questions of a larger research, part of which is this literature review focusing specifically on the first research question, namely on types and definitions of uncertainties in the context of communication and/or decision-making. The keyword search was automatic and included the following: ‘*Uncertain**’ AND ‘*Communicat**’ AND

Table 1. The keywords used in the literature search.

Main keywords ('AND') ³	Together with ("OR")	Resulting number of hits	
		Web of Science	Scopus
Uncertain*	Emergency	N = 44	N = 45
Communicat*	Radioactiv*	N = 4	N = 8
Decision*	Accident	N = 9	N = 35
Risk	Disaster	N = 28	N = 39
	Expos*	N = 82	N = 87
	Decommission*	N = 1	N = 1
	Nuclear	N = 17	N = 25

'Decision*' AND 'Risk' in combination with 'Emergency' OR 'Radioactiv*' OR 'Accident*' OR 'Disaster' OR 'Expos*' OR 'Decommission*' OR 'Nuclear' (see table 1).

The criteria applied during evaluation of titles and abstracts were: *the document had to be (1) a research article; (2) published in a peer-reviewed journal; (3) be related to uncertainties; (4) be related to decision-making and/or communication; (5) at least three of the keywords (two from main keywords and 1 from the combination section) have to be present in the abstract; and (6) has to be in the English language.*

The search resulted in 423 hits (see figure 1). After removing the duplicates, 224 articles remained whose abstracts were evaluated in order to be able to select the relevant ones for further analysis. The years in which the resulting hits are published range from 1992–2018. After screening the titles and abstracts, 60 articles were downloaded for further reading and analysis. During the detailed reading, 27 more articles were considered irrelevant either because they did not meet the selection criteria based on the full text or they were not useful for answering our research questions (e.g. they did not include/mention any definitions or types of uncertainty). Finally, we chose 33 articles for the final analysis (see annex 4 for a list of articles). The years in which these articles were published range from 2002–2018.

The analysis approach for the articles was two-fold. Using grounded theory as a method for rigorous analysis of the review (Wolfswinkel *et al* 2013), we first applied an inductive (bottom-up) approach, where we created and modified codes in NVivo² based on the content of the articles and then a deductive approach to analyse the relationship amongst the coding categories. This means that the first approach was open coding which was then followed by axial and selective coding (Wolfswinkel *et al* 2013). The coding process was carried out by the main researcher, but it has been supervised and confirmed by the other authors. To make sure the method of the paper meets the rich rigor, sincerity, credibility, transparency, resonance and ethical criteria, the recommendations for good qualitative research (Tracy 2010) as well as the PRISMA guidelines for scoping reviews (Tricco *et al* 2018) have been consulted. The data charting related to definitions and types of uncertainty were created inductively, without any pre-determination or expectation. Other data relevant for charting for this analysis included the publication year, study area, methodology, main variables, respondents and N (if applicable), the actor to whom a type of uncertainty belongs (this was decided based on the respondents participating in the study or when the author mentions a type of uncertainty belonging to a type of actor), as well as who is talking about a particular type of uncertainty (i.e. is it the laypeople

² NVivo is a software package for Qualitative Data Analysis (QDA). It supports QDA by managing and organising data, managing ideas, querying data, graphically modelling ideas and concepts as well as reporting from the data (Bergin 2011).

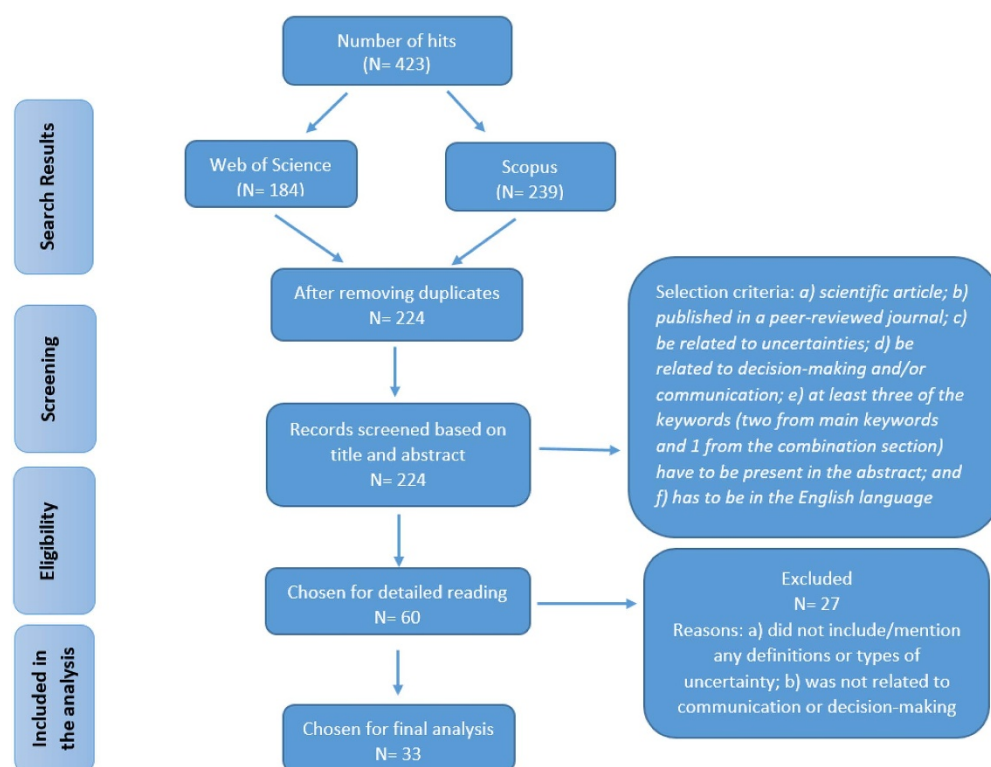


Figure 1. The literature search and selection flow.

talking about their uncertainties or the scientists saying what laypeople's uncertainties are?). The articles that served as material for the scoping review are listed in annex 4 (available online at: stacks.iop.org/JRP/40/612-631/mmedia).

4. Results

4.1. Definition of uncertainty

The results of this scoping review point out that out of 33 articles, only 19 of them include definitions of uncertainty. The other articles included in the analysis only mention types or use examples of uncertainty without explicitly defining what it means. Even these 19 articles define uncertainty in multiple and different ways.

As table 2 (see appendix 1) indicates, 6 out of 19 articles try to define uncertainty based on its *meaning* (i.e. what is meant by the concept of uncertainty). For example, (Walker *et al* 2003: 8) defines it as 'any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system', while (Han 2012: 165) argues that 'uncertainty is a "metacognition"—a thinking about thinking—characterised by self-awareness of incomplete knowledge about some aspect of the world'. Similarly, also related to perceptions, (Maxim *et al* 2013: 679) argues that 'uncertainty (...) refers to the situation that the body of evidence from scientific research is (perceived to be) inconclusive'. (Morris-Suzuki 2014: 349) makes a distinction between uncertainty and ignorance by saying that 'uncertainty is the situation

where the broad parameters of a risk are understood but science is not (or not yet) capable of accurately assessing the odds'. 'In a situation of uncertainty,' she continues, 'we are aware that there are variables we cannot predict; but in a situation of ignorance, we do not know what it is that we don't know'. (Harris 2015: 30) on the other hand, says that 'uncertainty implies ignorance'. Another definition is made by (Fearnley 2013: 1899), who explains uncertainty as a 'state of incomplete knowledge' involving complex, non-linear and open systems.

Speaking of incomplete knowledge, the majority of the authors (Levin *et al* 2004, Han 2012, Kox *et al* 2015, Romao and Pauperio 2016) see it as a *source* (i.e. cause or originating place of uncertainty) rather than a state or condition. Such sources of uncertainty mainly include uncertainties arising due to lack of knowledge (Thompson 2002, Levin *et al* 2004); due to randomness or variability (Kox *et al* 2015, Romao and Pauperio 2016); from the complexity of understanding different phenomena, from the difficulties encountered in decision-making processes (Laes *et al* 2005); arising from vague, ambiguous expressions (Han 2012, Romao and Pauperio 2016), etc. Based on these originating sources, authors then attempted to group different types (i.e. categories) of uncertainties and create typologies when explaining what uncertainty means.

The most commonly used typology is the *epistemic and aleatory uncertainty* distinction (Markon *et al* 2013, Doyle *et al* 2014, Knoblauch *et al* 2018). Apart from these two types, the typologies present in the literature cover different types of uncertainties as well.

Epistemic uncertainty is mainly related to the unknowns (Doyle *et al* 2014). It is defined as a state of mind and a reflection of our own incomplete knowledge (Thompson 2002, Eiser *et al* 2012, Harris 2015). Given that it is knowledge-based, it can be reduced with the gain of new knowledge (Knoblauch *et al* 2018). However, this is not always the case since obtaining more knowledge can point out some things we did not know or think of before, therefore increasing or adding more uncertainty (Walker *et al* 2003, van Asselt 2005, Romao and Pauperio 2016). Imagine you draw only red and blue balls from an urn. After 50 trials you believe that there are only blue and red balls in the urn. In the 51st trial you draw a green ball and immediately your inference about the system becomes fuzzier. Now you have to deal with three possible outcomes, and your probability assessment about the composition of the urn needs to be re-done and will expand your confidence interval for your assessment (Fox and Ulkumen 2011).

According to (Levin *et al* 2004: 36) epistemic uncertainty refers to the degree of belief and credibility and is mainly expressed with the statements 'has been considered by some', 'it is generally believed' and 'it appears that'. Hence, the indicators of epistemic uncertainty are words and expressions that indicate less than full confidence in, or commitment to, the content of a statement (Levin *et al* 2004).

Aleatory uncertainty is also referred to as stochastic uncertainty, which is random (Doyle *et al* 2014, Maxim 2014, Romao and Pauperio 2016) and dependent on the nature of the things for which we seek knowledge (Eiser *et al* 2012). (Knoblauch *et al* 2018) argue that this type of uncertainty is irreducible. (Maxim 2013: 685) explains it as 'the randomness of natural differences between individuals in, e.g. their reaction to chemicals', or 'the time between the consecutive occurrence of disasters such as earthquakes of a given intensity' as (Romao and Pauperio 2016: 4) state. Aleatory uncertainty can either be based on statistical distributions (such as throwing a dice) or variability without any recognisable statistical pattern (occurrence of earthquakes). The latter may be true because of the rareness of the event that does not allow a statistical representation, or it seems to be totally randomised without any regularity in occurrence or severity. Aleatory uncertainty is also known as natural *variability*, which is especially applicable in human and natural systems and concerning social, economic and technological developments (Walker *et al* 2003). (Bier and Lin 2013) mentioned that variability reflects differences amongst the members of a heterogeneous population. A similar definition

was made by (Thompson 2002) who says that variability refers to real and identifiable differences between individuals within a population addressed by the risk assessment. However, this author argues that uncertainty and variability are two different things and they have to be distinguished (Thompson 2002). Variability refers to real differences between individuals of a population. Therefore, decision-making under uncertainty requires judging how probable it is that risks will be over- or underestimated for every member of a population, while variability requires taking into account the certainty that ‘different individuals will be subjected to risks both above and below any reference point one chooses.’ (Thompson 2002: 648).

The distinction between epistemic and aleatory uncertainty is, however, not always evident. (Bier and Lin 2013) mention two other terms that are used in the literature as types of uncertainty. These include ‘outcome uncertainty’ and ‘assessment uncertainty’. Outcome uncertainty is related to what might happen and with what probability and, according to (Bier and Lin 2013), this source of uncertainty reflects both state-of-knowledge uncertainty and population variability, while putting together epistemic and aleatory uncertainty. Assessment uncertainty, on the other hand, is related to the state-of-knowledge uncertainty, namely, how much the results of the analysis might change with additional information (Bier and Lin 2013), which in this case is just another term used for epistemic uncertainty. Likewise, (Laes *et al* 2005) mention the term ‘cognitive uncertainty’ when referring to ‘epistemic uncertainty’. They argue that cognitive uncertainty may be generated as the understanding of phenomena becomes even more difficult, and at the same time, principal limits of knowledge emerge. This is often called the ‘problem of expertise’ or lack of uncontested factual knowledge with which decision-makers are faced (Laes *et al* 2005).

Ambiguity has been mentioned as another type of uncertainty by many authors. This is when a word can be used in more than one way, and it is not clear in which way it is being used from the given context (Markon *et al* 2013). It denotes the possibility of interpreting knowledge in different ways or drawing different normative conclusions from an identical set of evidence. The same source is termed as ‘contentual uncertainty’ by (Levin *et al* 2004), while (Kox *et al* 2015) divide it into ‘context-dependence’ which points to the fact that a statement can have different meanings in different contexts; ‘underspecificity’, which shows that the term is not as specific as needed; and ‘vagueness’, which arises from unspecific use of a term in a borderline-case sense (Kox *et al* 2015). (Romao and Pauperio 2016) define this source as ‘linguistic’ uncertainty which differs from aleatory and epistemic uncertainties since it does not belong to the data under analysis, and it is not created by processing available data. Instead, linguistic uncertainty is created when trying to express information using non-quantitative metrics (Romao and Pauperio 2016). There are arguments that ambiguity is different to uncertainty, the former implying a lack of meaningful interpretation and the latter defined as a shortage of information. But (van Asselt 2005) argues that ambiguity (interpretational plurality) is a phenomenon of uncertainty rather than a distinguished part.

Another type mentioned in the literature is *decision* uncertainty. It occurs in the process of decision-making based on the interpretation of results that were expressed and communicated. In this process, different individuals can have different interpretations of the same data due to subjective judgment or differences in values, beliefs and preferences and, therefore, make decisions in different manners (Romao and Pauperio 2016). Similarly, (Laes *et al* 2005: 358) use the term ‘pragmatic uncertainty’ to explain ‘the uncertainties resulting from the difficulties encountered in policymaking processes to reach conclusions and to implement decisions in a turbulent social environment’. As is the case with the other types of uncertainties, decision uncertainty has also been termed in different ways and sometimes even blended with ambiguity, such as in the case of low-dose (ionising and non-ionising) radiation (Renn 2008b).

(Maxim 2014) also argues that there are more types of uncertainties in addition to the ‘epistemic–aleatory–ambiguity’ distinction. These include *technical uncertainties*, which are mainly technical errors caused by imprecise instruments or measurement methods; *methodological uncertainties* which include methodological challenges, such as making assumptions when knowledge is missing or choosing from amongst several available methods for assessing a parameter; *normative uncertainties*, which include interpretation of raw data and conclusions about the level of evidence they provide; as well as *communication uncertainties*, which include how completely and understandably the research is reported (Maxim 2014: 5).

It is also important to distinguish *expressed* uncertainty from *perceived* uncertainty because the scientific message transforms as it is communicated from the emitter (i.e. the scientist) to the receiver (i.e. laypeople) (Maxim *et al* 2013). Expressed uncertainty includes situations when a scientist says they do not know; a scientist says they are not sure/confident in their results; or different scientists disagree, even if each is fully confident in their assertions (e.g. the debate related to Genetically Modified Organisms) (Maxim *et al* 2013). On the other hand, perceived uncertainty includes situations in which laypeople ask questions about the scientific information received; have doubts about or lack trust in the scientific information received; criticise the assumptions and choices made by scientists when producing or interpreting information; point out contradictions amongst experts; and point out the fact that they do not understand the scientific information received (Maxim *et al* 2013).

4.2. Uncertainties across different actors

In this section we present the results of the research question related to different types of uncertainties across different actors, such as the scientific community, decision-makers and the laypeople.

4.2.1. Uncertainties amongst the scientific community. In the studies that employ scientists as respondents ($n = 15$), or mention the uncertainties of the scientific community, as explained in table 3 (appendix 2), the majority of the uncertainties mentioned are of a methodological nature. For instance, in a study related to emerging contaminants, based on in-depth interviews with scientists, (Cordner and Brown 2013: 469) came to the conclusion that scientific uncertainties are caused by four sources of ethical concerns: ‘(1) choosing research questions or methods, (2) interpreting scientific results, (3) communicating results to multiple publics, and (4) applying results for policymaking’. Similarly, based on a survey with 34 natural hazards experts, (Kunz *et al* 2011: 1737) argue that uncertainty is related to the components of data quality, such as error or accuracy, precision, completeness, consistency and currency, as well as other elements such as credibility, subjectivity and interrelatedness. (Levin *et al* 2004: 33) echoes this based on a content analysis where he relates scientific uncertainty to the study methods, namely to the quality and relevance of the study design, extrapolations, data gaps, the way the study is performed and how the results are reported. According to (Oberg and Bergback 2005) acquiring more and better data can reduce uncertainty. This applies to uncertainty in ‘model structure, parameter estimates and exposure scenarios’ (Oberg and Bergback 2005: 215). Model and parameter uncertainty are also mentioned by (Linkov *et al* 2006) in their study using model inter-comparisons to address model uncertainties.

Another type of uncertainty mentioned by the scientific community present in the literature is related to the communication process. Some aspects of this type of uncertainty, as (Han 2012) states based on a literature review, are conceptual and relate to questions about the meaning and nature of what we are communicating. Other aspects are more practical, namely

how to communicate these uncertainties? An additional example comes from the study of (Drew *et al* 2003: 266) based on focus groups with scientists arguing that there is a need for more knowledge and education on how to raise the public understanding of risk by explaining the differences between uncertainty and variability in data.

Furthermore, there are *ethical* aspects related to communicating information that is relevant but which is subject to potential harm or consequences (Han 2012: 155). A similar conclusion has been drawn by (Fearnley 2013) following her in-depth interviews with 93 scientists. A quote from a scientist in her study states that they are torn between the desire to remain neutral by issuing only the scientific information versus providing additional information on the hazard and risk which is considered essential. The practice of uncertainty communication is also associated with conflicts on whether to give recommendations on decision-making or not. One scientist in this study stated: 'I don't think that we scientists should strive to make the jobs of public officials any easier. I think that we should tell them honestly what we don't know as well as what we know, they have tough choices to make and should not be spoon-fed' (Fearnley 2013: 1906). Another issue mentioned in a literature review from (Harris 2015) related to communication of uncertainties is the impact that media can have on this communication process. Scientists reported that their statements get misquoted in the media stories and that reporters are not prepared or aware of the subject they are writing about (Harris 2015: 20).

Furthermore, there are epistemic and aleatory uncertainties mentioned amongst the scientists in the literature, such as uncertainty to low-dose risks (e.g. linear no-threshold theory) (Mossman 2009: 104); variability amongst the risks posed by different nuclear power plants; epistemic uncertainty about the average risk in a population of similar power plants (Bier and Lin 2013: 1900); uncertainty over the probability of an event as well as uncertainty over the value of the consequences, mainly because 'value' can have different meanings (Eiser *et al* 2012: 7).

Decision-related uncertainties are also mentioned in the literature related to the scientific community. For example, in a study using interviews with forecasters about flash flood risks, (Morss *et al* 2015) found that forecasters are uncertain in monitoring and predicting these events. This poses a problem in deciding when to release warnings. For example, if a warning is released too early, you risk raising unnecessary panic (Kox *et al* 2015). On the other hand, as a quote in the study of (Morss *et al*, 2015: 2021) illustrates, 'waiting for clearer evidence in a rapidly evolving, highly uncertain situation costs you lead time and may even lead to a missed warning for an event'. Significant uncertainty can also arise due to problems with collaborations across agencies, understanding of each other's responsibilities (Rimstad and Sollid 2015) and interdependencies. This is particularly evident in emergencies characterised by high pressure, short time, high risk, consequences and stress (Doyle *et al* 2014: 76).

4.2.2. Uncertainties amongst the decision-makers. The studies analyzing the uncertainties of the decision-makers ($n = 8$), report different types of uncertainties, such as (no rank order) uncertainties related to decision-making, public reaction, communication and collaboration, ethical and economic aspects. These studies are reported in table 4 (appendix 2).

In their study regarding uncertainties in model-based decision support (Walker *et al* 2003: 6) mention decision-related uncertainties, such as how certain should one be to ban harmful activities and who should bear the responsibility of the risks of making the wrong decision. Similar issues have been raised in the study of (Govaerts 2004: 33) about handling uncertainty in off-site emergency management. For example, he argues that the basic dilemma of the Three Mile Island accident, namely, how to manage uncertainties (e.g. when the reactor building is the only intact barrier) in decision-making remains unaffected. (Morss *et al* 2015) illustrate

this with a quote coming from the interviews with one of the public officials participating in their study: ‘if you get it right but you waited too long, it’s not going to be as effective. But if you go too early and it turns out not to have been the disaster that you were expecting, then people will lose trust in that system’ (Morss *et al* 2015: 2021).

Uncertainties related to *public reactions* are also mentioned quite often. One of the respondents in the study of (Morss *et al* 2015: 2023) states the following: ‘I could stand out there with a bullhorn and say: “The sky is falling,” and if no one is paying attention to me, they are going to stay in harm’s way The [citizens have] to help me help them’. A similar argument is brought up in the study of (Fairchild, Colgrove, & Jones 2006: 961) related to decision-making and uncertainty in emergencies where they mention that such situations are always accompanied with some people who think they are ‘tougher than the storm’. An argument related to the public’s understanding was raised in the study of (Cordner and Brown 2013: 484) based on in-depth interviews where a regulator states that the public does not understand that the presence of a small dose does not necessarily mean that it is harmful.

Communication and collaboration issues are brought up in the study of (Kox *et al* 2018: 118) based on interviews with 27 German civil protection authorities. They argue that some of the uncertainties are associated with miscommunication and misunderstanding of the situation. This was also mentioned by (Laes *et al* 2005), where they mention ‘[...] different framing of the problem; institutional barriers; lack of communication; strategic use of scientific assessments by different stakeholders; and insufficient knowledge of scientific assessments’ as types of uncertainties (Laes *et al* 2005: 357). The absence of clear lines of command further complicates the response to emergencies (Fairchild *et al* 2006).

The uncertainties of an ethical nature are also often mentioned in the literature related to decision-makers. For instance, what to do with people who do not follow the recommendations regarding evacuation in an emergency, as well as what to do with the sick and disabled people in such situations? It might be more harmful for them if they are moved (Fairchild *et al* 2006: 964). Another kind of uncertainty of ethical nature is mentioned by (Laes *et al* 2005: 398) when studying the uncertainties in the nuclear policy, which is the ethical justification to continue relying on nuclear power from a perspective of sustainable development. Such issues are termed as ethical ambiguities in the literature.

Last, but not least, uncertainties of an *economical* nature are mentioned by decision-makers. For instance, in the case of nuclear policy, there are uncertainties related to ‘the costs of decommissioning, costs of high-level waste management, but also the real costs of the business-as-usual scenario, etc’ (Laes *et al* 2005: 366).

4.2.3. Uncertainties amongst the laypeople. The most-often-mentioned uncertainties in the articles analysing laypeople’s uncertainties ($n = 8$) are related to *trustworthiness* (e.g. whom to trust) which is mostly linked to the information provider (see table 5, appendix 2). For instance, in the study of (Markon *et al* 2013: 320) the participants of the focus groups show a high level of distrust towards the information, either by stating that they cannot believe it when it comes from the government or by stating that the information given is always biased, namely for the benefit of someone who has invested in such an affair. One of the respondents in this study states this point more firmly when talking about the US five-level national alert regarding health risks: ‘You know for a while there was the red light, the yellow light, the blue light, and they did that so often that you could not care less at the end, so I don’t see the purpose of that, and I think it’s just propaganda, a lot of it’ (Markon *et al* 2013: 323).

A similar statement came from focus groups with citizens in the study of (Maxim *et al* 2013), where one citizen argues that she does not believe the results coming from the workers

of the industry because ‘... they are obliged to produce results [...] and keep people calm’ (Maxim *et al* 2013: 685). Furthermore, in emergency situations, when there are competing messages, social media interferes making it difficult to decide the difference between accurate information, rumours and malicious information (Conrado *et al* 2016: 171).

Distrust towards government’s actions and position also resulted in the highest values (45.2%) in the study of (Tateno and Yokoyama 2013) when analyzing the reasons for public anxiety and uncertainties related to low-dose radiation based on internet surveys. Feeling uncertain and not trusting the information related to risk proved to have an impact on respondents not changing their behaviour regarding health risks (Blanchemanche *et al* 2010: 287).

Laypeople also report uncertainty in the form of *emotions* and *feelings*, such as fear, frustration, anxiety and guilt. This can be illustrated with a quote from a study by (Abbott *et al* 2006: 111) interviewing citizens of Russia, Ukraine and Belarus after Chernobyl: ‘It was terror. It was terror. It was scary. I did not know what to do, where to run, to go and then I was perplexed. Why did it happen like that and why was everything so calm.’ Uncertainty about the future is also present in the form of fear of diseases given the high mortality rates and children born unhealthy after Chernobyl (Abbott *et al* 2006: 112).

Similarly, when providing the participants of focus groups with a video containing scientific uncertain information regarding endocrine disruptors (Maxim *et al* 2013) found that the participants reported fear based on the negative effects of the study, although they were not certain. This fear was for most of the time linked with feelings of guilt, responsibility and powerlessness, especially when having to make decisions for someone else (e.g. children) (Maxim *et al* 2013: 690).

Ambiguous anxiety is also mentioned by laypeople when asked about their low-dose radiation uncertainties (Tateno and Yokoyama 2013: 14).

When asking experts on what the uncertainties of the laypeople are in their opinion (Morss *et al* 2015: 2023) found that based on experts, the most important aspects that the laypeople want to know are: the nature of the hazard; where, when and how it may happen; how to receive and interpret information and what to do (and not to do) in such situations. This holds for the uncertainties related to *lack of information*, as can be illustrated by a quote from one citizen: ‘Essentially nobody solves the Chernobyl problem. Everything is garbled because science doesn’t know how to react to it and no one cares about the people living in the zone. No one can tell us what will happen’ (Abbott *et al* 2006: 111). Another concern raised from focus groups with the general public is ‘[the] need for better, more timely, notification and general information about nuclear waste transport’ (Drew *et al* 2003: 266).

However, if there is ambiguous or contradictory information, this will cause further uncertainties for the laypeople. For instance, risk information that was either too specific or missed certain elements, caused ambiguity amongst respondents, thereby making them unable to estimate the probability of the risk (Blanchemanche *et al* 2010: 287). A similar issue is raised in the study of (Harris 2015) related to the communication of uncertainties, where the media reporters argue that ‘sometimes scientists speak like scientists and not like people ... you know, some people don’t know what low pressure means, what high pressure means, and some people don’t know and don’t care what millibars are’ (Harris 2015: 20).

4.3. Uncertainties across different study areas

The scientific community in the radiation risk studies reports mainly methodological uncertainties, epistemic and aleatory uncertainties (these not being exclusive and sometimes related to each other). These include uncertainties to low-dose risks (linear no-threshold theory) in the field of radiation risk assessment (Mossman 2009); variability amongst the risks posed

by different nuclear power plants in the nuclear field (Bier and Lin 2013); how to help raise public understanding of risk in the nuclear waste transportation field (Drew *et al* 2003); inter-individual, spatial and temporal variabilities regarding contaminated lands (Oberg and Bergback 2005); as well as model and parameter uncertainties in radionuclide distribution modelling (Linkov *et al* 2006).

As can be seen in table 6 (see appendix 3), more or less the same types of uncertainties are reported amongst the scientific community in other study areas as well, such as volcanic hazards (Fearnley 2013, Doyle *et al* 2014), flash flood risks (Morss *et al* 2015), weather warnings (Kox *et al* 2015), medical emergencies (Rimstad and Sollid 2015). Such uncertainties are related to the methodological aspects, such as quality, relevance and interpretation of the results (e.g. unexplained variance, reliability, random variance, etc (Sjoberg 2003)); epistemic uncertainties, such as the likelihood of the happening of certain events; as well as communication and decision uncertainties as to how to issue information that is subject to uncertainty, and when to issue warnings, making sure that it is neither too early nor too late.

The decision-makers in the radiation risk research are faced with uncertainties related to decision-making, such as how to manage uncertainties in decision-making processes (Govaerts 2004); economic aspects, such as the costs of decommissioning and nuclear waste management (Laes *et al* 2005); ethical aspects related to the justification of reliance on nuclear energy from a sustainable development perspective; as well as communication aspects, such as a lack of communication and strategic use of the scientific assessments and information. Similar types are present in the other fields of risk research analysed in the literature review. Apart from the above mentioned types, one type of uncertainty that was not specifically mentioned in the radiation risk research but is mentioned in other fields, such as emergency evacuations (e.g. hurricanes) (Fairchild *et al* 2006) and emerging contaminants (Cordner and Brown 2013), is uncertainty related to public reactions. As explained earlier, this type of uncertainty deals with the public acceptance and following of the recommendations given. It is worth mentioning though, that grey literature (e.g. reports, narratives) have taken these uncertainties into consideration (IAEA 2016, Raskob 2017, Guillevic *et al* 2018), but they were not present in the scientific literature in which we were particularly interested in.

Similar to the previous actors, the uncertainties of the laypeople do not differ across different study areas either. Lack of trust is one of the most-often-mentioned types of uncertainties, both in the case of Chernobyl and Fukushima accidents (Abbott *et al* 2006, Tateno and Yokoyama 2013), as well as in other risks such as endocrine disruptors (Maxim *et al* 2013). Uncertainty in the form of emotions and feelings is also mentioned in different study areas. This is mainly related to the fear of getting diseases (e.g. cancer), worry about the future and feeling guilty for the decisions made for other people. Lack of information is also reported quite often in different fields of risk research. This is linked to the need for timely, accurate and unambiguous information.

5. Discussion and recommendations

Our results point out that there is no scientific consensus on definitions of uncertainty. This is not entirely new as it was partly expected based on the arguments of multiple authors that uncertainty definitions are numerous and diverse (Walker *et al* 2003, Maxim 2014). However, we argue that if it is not possible to use a common/universal definition of uncertainty (given the big differences across disciplines), at least the authors/users of uncertain information have to clearly describe what they mean by the concept of uncertainty.

Something that emerged as new from our results and that might serve as an explanation for this diversity in the definitions of uncertainty is that only a small number of the articles define uncertainty based on its meaning. The other articles define it based on causes/sources or types, and it is sometimes difficult to distinguish between these categories when trying to formulate a definition of uncertainty. For instance, lack of/incomplete knowledge is sometimes seen as a source of uncertainty (uncertainty generated due to incomplete knowledge), sometimes as a type (epistemic uncertainty) and sometimes as a definition of uncertainty itself (state of incomplete knowledge). What can be an uncertainty for a scientist (e.g. theories of low-dose radiation), can be a cause of uncertainty for decision-makers (e.g. what to take into account when assessing risks and making decisions) and, as a consequence, it can result in worry or concerns amongst the laypeople (Vaiserman *et al* 2018). That being said, uncertainty in knowledge can be present independently of who the user or the provider of information is. But if we look at uncertainty in communication, another explanation for this diversity of definitions can be offered: namely, the different uncertainties between the information ‘provider’ and information ‘receiver’ (Maxim and van der Sluijs 2011).

This led us to analyse our second research question, namely whether there are different types of uncertainties across different actors that are present in the analysed scientific literature. The results regarding this question show us two things: first, the majority of the literature analysed is focused on the uncertainties of the scientific community, while the uncertainties of the decision-makers and those of the laypeople (i.e. information receivers) are analysed to a much lower extent. The limited attention to the latter actors also shows that research is mainly focused on the top-down communication process (information issued by scientists to other actors) when studying uncertainty communication and decision-making under it. Second, there are different types of uncertainty that different actors are faced with. As can be seen in table 6 (appendix 3), the uncertainty of the scientific community is more data and methodology-driven (e.g. dose-response relationships), those of the decision-makers are more related to the likely consequences of decision options and public reactions while laypeople’s uncertainties are mainly related to the trustworthiness of experts or the emotional potential of special risk exposure. These results do not mean that the scientific aspects of the received information are not questioned by the laypeople. On the contrary (Maxim *et al* 2013: 684) found that the respondents participating in their study mentioned uncertainties regarding causal relationships, data and methodology, such as limited samples and choice of variables. However, such uncertainties are mentioned much less in the literature related to the uncertainties of the laypeople, and they are not as ‘specialised’ as the experts expect them to be (Maxim *et al* 2013: 685).

After analysing uncertainties across different actors, we then analysed whether there are different types of uncertainties present in different study areas (radiation versus other natural and man-made hazards) analysed in the literature. The results show that the types of uncertainties present across these study areas are relatively similar and that the main difference is across actors rather than across study areas. However, we must point out that here we only analysed articles dealing with risks such as natural and man-made hazards (articles more related to natural sciences), so we cannot come to generalisations about these results across all disciplines, such as the risks present in the social sciences discipline.

To explain the relevance and implications of these results for risk and uncertainty communication related to radiation protection, we need to restate the main objective and rationale behind communicating uncertainties, which is to contribute to informed decision-making amongst the receivers of the information (Patt and Weber 2014, Doyle *et al* 2014). To reach this objective, as our results suggest, we need to shift the attention towards knowing what kind of information is wanted and needed by the information receivers. We realise that scientific literature (articles used for this review) mainly addresses the scientific community and rarely

involves risk communication directed towards general audiences. However, the main argument generated from this review is that scientific literature needs to study the uncertainties of information receivers more. This can be done empirically by using surveys, experiments, focus groups, content analysis, etc, which use information receivers as respondents. These studies would still be a part of scientific literature and communicated to other scientists. But the difference would be that they take different actors into account. Based on these results we argue that it is not about to whom these uncertainties are communicated, but rather to first understand to whom they belong. Only when we understand the uncertainties of the different actors, can we address them through communication and contribute to better decision-making.

Failure in doing so results in a lack of laypeople's trust in scientists, who seem not to know the needs of laypeople, and a lack of scientists' trust in the public, who seem unable to understand uncertain information (Fischhoff 2012). This is clearly expressed in the study of (Harris 2015: 20) where the scientists argued that their statements get misquoted in the media stories and that reporters are too poorly prepared, while the media reporters, on the other hand, argued that 'sometimes scientists speak like scientists and not like people ... some people don't know what low pressure means, what high pressure means, and some people don't know and don't care what millibars are'. This means that although aiming to contribute to informed decision-making, communicating scientific uncertainties does not necessarily satisfy or decrease the uncertainties of laypeople.

Because this work is part of a bigger project (dealing with radiological emergencies, radiological exposure situations and decommissioning processes) we used a set of specific keywords and strict inclusion criteria to obtain articles for analysis. This made the number of articles analysed rather low (33 articles) and made it impossible to take into account all the literature on the health effects of radiation, which is scattered over a big range of disciplines. For the purpose of this study, we preferred to focus on these three cases, which are of crucial importance, and to which not too much attention has been given. However, it would be very useful for future research to take into account all the literature on the health effects of radiation, regardless if uncertainty is specifically mentioned in the text (which was one of the main inclusion criteria of this review). Furthermore, given that the main focus of the paper is to understand whether and how different scientific articles define uncertainty and which types of uncertainty do they mention or pay attention to, creating a new typology in order to group these definitions and types together would be out of the scope of this review and would only add one more typology to the already vast and scattered pile of the existing ones.

5.1. Recommendations for radiation protection community

While most of the focus in the radiation protection literature is on the technical uncertainties, the uncertainties of the laypeople are much more overlooked. Consequently, research is mainly focused on the top-down communication process (information issued by radiation protection experts to other actors) when communicating about and deciding on radiation protection issues. Based on these findings, we provide some preliminary recommendations regarding research on uncertainty related to radiation protection, as well as communication practices.

- Uncertainties in radiation protection research and practice need to be admitted and communicated. They should be clearly mentioned in printed format (e.g. scientific articles, newspapers, etc), online (e.g. information available on the internet, different websites, online media of platforms), broadcast (uncertainties or limitations should not be excluded when

communicating information through the media) and verbal conversations between information providers (e.g. radiation protection experts) and information receivers (e.g. laypeople and decision-makers).

- The radiation protection community needs to take into account the uncertainties of the information receivers. Uncertainty assessors and/or uncertainty communicators need to be attentive to the characteristics of the target audience in order to address their fears and concerns. This means that different levels of knowledge, expertise and familiarity with terminology need to be taken into account.
- The uncertainties of the information receivers themselves, as well as their relationship to what is being communicated (e.g. is there an emotional link, such as the fear of cancer from low-dose radiation) need to be further investigated and addressed.
- Uncertainty assessors (e.g. radiation protection experts) and/or uncertainty communicators (risk management experts, medical personnel, communicators acting on behalf of the institutions/organisations) need to clearly communicate about uncertainty, its source (i.e. why is there a lack of insufficient/ambiguous knowledge?), and magnitude (e.g. is it a small imprecision or a large gap in knowledge?).
- Uncertainty needs to be clearly explained. This can be done in different formats such as: numerically, verbally or by means of visualisation.

6. Conclusions

After analysing 33 scientific articles based on a selected set of keywords, directly or indirectly related to radiation risks, we found that there is no common agreement regarding uncertainty definition and these definitions differ across studies. Furthermore, we found that different actors are faced with different types of uncertainty. While the uncertainties of the scientists are more related to methodologies and results, those of the decision-makers are related to decision-making issues, public reactions and economic issues, and the uncertainties of the laypeople are related to a lack of trust, lack of information and appear in the form of emotions and feelings. What is more, we found that the majority of the articles focus on the uncertainties of the scientific community, while those of the decision-makers and the laypeople are taken into account a lot less. While this finding is not entirely new, it deserves more discussion in the radiation protection community.

Based on these findings we argue that before proceeding with communication processes, we need to acknowledge the fact that uncertainties diverge (and potentially broaden) from scientists to decision-makers and finally to the laypeople. In a two-way communication process, we have to speak each other's language for the communication to be successful. Given that the main goal of uncertainty communication is to get the public to understand, trust and make proper use of the information provided, more attention needs to be paid to the side of the information receivers (in this case decision-makers and laypeople) in order to understand what information they want and need to make informed decisions. When the scientific uncertainties of the radiation meet the very different uncertainties of everyday life, the scientific logic diverges, creating deep problems regarding communication and understanding. This is relevant not only to the nuclear or radiation aspects, but also to how scientific knowledge is constructed and communicated in general (Morris-Suzuki 2014). Similar to risk (Renn 2004), we argue that to bridge this gap of different perceptions and definitions of uncertainty between different actors, two-way communication has to be initiated between scientists, decision-makers and the laypeople. This would help by offering different perspectives and creating mutual understanding, as well as building trust amongst the actors.

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