



Deliverable 6.8

Behaviour psychology related to value-action gap in the field of Radon and NORM: Final report

Work Package **6**



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Executive summary of the RadoNorm project

EU member states, associated countries and the European Commission are implementing the European Basic Safety Standards Directive for radiation protection. The EU-funded RadoNorm project focuses on all radiation risk management cycle levels for radon exposure, as well as situations of exposure to naturally occurring radioactive materials (NORM). The project intends to reduce scientific, technical and societal concerns by introducing research and technical developments, integrating education and training (E&T) and disseminating the results of the project through targeted actions to the public, stakeholders and related institutions. RadoNorm directs research and development on all levels of the management cycle, combines biomedical and ecological research with mitigation development and social science research and brings together researchers from national radiation protection entities, universities and SMEs.

Executive Summary of the Deliverable

WP6 investigated strategies to address the value–action gap across different stakeholder groups. This deliverable presents two research cases: the first focuses on radon, while the second examines NORM.

The radon case: radon is a major indoor air pollutant that poses a significant risk of lung cancer to those exposed in their homes. While mitigation of high radon levels in homes has been shown to be effective, home mitigation rates remain low. This study examines the barriers and facilitators to radon mitigation in homes from the perspectives of authorities responsible for radon risk management, the mitigation industry (contractors), and residents in four European countries (Belgium, Ireland, Slovenia, and the UK) with high radon risks and low mitigation rates. A multi-method approach was used to gather data from various stakeholders, including online surveys, content analysis of legal documents, group interviews, workshops, and focus groups. Authorities, contractors, and residents identified various facilitators to radon mitigation, including legal requirements for mitigation, awareness campaigns, low mitigation costs, availability of financial support, accreditation of mitigation contractors, and a perception of radon as a health threat. However, barriers to mitigation were also identified, such as a lack of awareness, fragmented mitigation processes, and inadequate communication between stakeholders. The study highlights the complexity of the radon mitigation process and suggests that interventions aimed at increasing mitigation rates should target stakeholders beyond just residents, such as constructors, health professionals, and policy makers. An integrated approach to radon mitigation, from policy to provision, is necessary to effectively lower levels of this indoor air pollutant.

The NORM case: environmental remediation projects imply a process fraught with uncertainties. While this is a truism, uncertainties faced by different stakeholders before, during, and after a remediation process have not been systematically and empirically investigated. Hence, the goal of this study is to identify how stakeholders, including affected populations (residents), remediation experts, authorities, industry, and the mass media, perceive and experience uncertainties encountered during long-term environmental remediation processes at mixed chemical-radiological contaminated sites caused by industrial practices. For this purpose, the study employs a mixed methods approach at two sites in Flanders, Belgium contaminated by radioactive materials from radium production and the phosphate industry: this includes media content analysis (N=164 articles published over three decades), semi-structured interviews with residents from affected areas (N=24), and exploratory questionnaire followed by a panel discussion with experts, industry representatives, remediation experts, and authorities (N=10). The study reveals that uncertainties vary widely among stakeholder groups and over time. Stakeholders emphasise different aspects of uncertainty, from management and legal issues to public health concerns. Residents show higher trust in authorities and operators to solve the uncertainties,

contrasting with experts' focus uncertainties related to remediation techniques, societal challenges like conflicting needs and expectations and future land use. Each contaminated site's uncertainties are shaped by historical, socio-political, and economic contexts. This study is valuable for those interested in stakeholder involvement in decision-making on environmental issues, as well as for those examining the societal aspects of decision-making in radiation protection.

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1. A psycho-social-environmental lens on radon air pollutant: authorities', mitigation contractors', and residents' perceptions of barriers and facilitators to domestic radon mitigation

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1.1 Introduction

Radon is a naturally occurring radioactive gas that can accumulate in indoor environments and is one of the major indoor air pollutants (1). According to the World Health Organization (WHO), radon is one of the leading causes of lung cancer: it is estimated that it causes around 21,000 deaths annually in the European Union alone (2). Although radon exposure in the home increases the risk of lung cancer, this risk can be managed by testing and mitigation. Unfortunately, low mitigation rates of dwellings with high radon risks are reported in all countries in Europe (3, 4) and worldwide (5–7) indicating a value-action gap (8). The value action gap is a well-established phenomenon, where attitudes about protecting one's health do not result in the protective behaviour being performed.

The Council Directive 2013/59/Euratom Basic Safety Standards (9) mandates that European Union Member States (EU MS) establish National Radon Action Plans (RAPs) to reduce radon exposure and ultimately the risk of lung cancer. Annex XVIII of the Directive provides a list of items to be considered by authorities in preparing a RAP. RAPs should include measures such as radon mapping, the promotion of radon resistant construction techniques to prevent radon ingress into new buildings and the provision of information to the public on radon risks and mitigation measures. Each EU MS should establish its own national reference levels for the annual average concentration of radon in air in indoor workplaces and dwellings. National reference level shall not be higher than 300 Bq/m³ radon concentration for both, dwellings and workplaces (9); however, in some countries, for instance Ireland, the reference level is 200 Bq/m³. The WHO recommends that countries adopt reference levels of the radon gas of 100 Bq/m³. If this level cannot be implemented under the prevailing country-specific conditions, the WHO recommends that the reference level should not exceed 300 Bq/m³ (2).

Where radon levels in buildings exceed the reference level, mitigation can be performed to the building. However, evidence consistently indicates that testing for radon and subsequent home mitigation rates are generally low in many countries, even if indoor radon concentrations can be cost-effectively reduced (10). It is worth noting that existing research has primarily focused on the impact of radon awareness campaigns and risk perception on increased radon testing (11, 12), with fewer studies of interventions reporting on indoor radon mitigation (13, 14), overlooking value-action gap related to mitigation. There is a need to better understand the factors that hinder and facilitate radon mitigation after receiving a high indoor radon test result (15). However, in order to develop such an understanding, it is essential that a broad perspective is taken.

The successful mitigation of radon in dwellings requires coordination and cooperation among multiple stakeholders, including authorities, the mitigation industry, and residents or owners (16–18). To date, research has primarily examined the radon mitigation from the perspective of the residents but has neglected the role that other stakeholders play in facilitating mitigation. Legal authorities are responsible for regulation of the indoor radon exposure and the implementation of national strategies (9). The mitigation industry conducts the technical work to reduce radon levels in existing buildings. Residents

or owners of domestic buildings are responsible for testing for radon concentrations and mitigating the dwellings if exceeded rates of radon detected (19).

Research worldwide (20–24) shows that during the past decade an important component of radon control strategies directed at the public has been to educate, inform, encourage, persuade and engage the public to measure radon in their homes and to mitigate the dwelling if considered necessary; however, the “voluntary public responses to these efforts have been disappointingly low” (3).

Radon awareness campaigns typically used fear appeal and technical knowledge about radon (23) to target individuals to encourage them to test and, where appropriate, mitigate. Although some research focuses lack of knowledge of radon as the main issue to address, simply increasing awareness, knowledge or risk perception does not necessarily improve risk mitigation behaviours (9, 25). Education alone is not sufficient for increasing health-protective behavioural action (26, 27); people are complex and have factors that interact, influencing decisions on preventive action (28). Consequently, research needs to examine the lack of mitigation action from a more comprehensive psycho-social-environmental lens. A broad range of behavioural (e.g., perceived lack of time), psychological (e.g., self-efficacy), educational (e.g., low level of educational attainment), socio-economic (e.g., low income) and social factors (e.g., lack of home mitigation performed others in similar high radon risk area) may influence radon mitigation rates (6, 29–34). However, focusing only on the individuals neglects the context in which the individual acts and the critical role that other people and organisations/agencies in their environment have on decision-making by residents regarding radon. The individual's environment comprises of important others in the community (e.g., healthcare professionals) who may encourage radon mitigation, as well as the availability of those providing radon mitigation services (e.g., contractors). In addition, the policies and practices of radon responsible authorities at a national or state-level will also impact on the individual's decision options and consequently mitigation rates.

The objective of this paper is to shed light on the critical issue of successful mitigation of radon in dwellings by examining the barriers and facilitators from the perspectives of key stakeholders from various levels: responsible authorities, the mitigation industry (contractors) and the residents. The study takes place in four countries with high radon risks and low mitigation rates, namely Belgium, Ireland, Slovenia and the United Kingdom (UK), with similar radon risks and diverse approaches to radon risk management in a period between 2022 and 2023, during a period of intensive implementation of a new legislation in the four countries (35) (see Table 1.1 for key comparisons).

This study is the first of its kind to investigate these stakeholders and countries simultaneously and aims to provide empirical evidence to support policy and decision-making processes in the implementation of new legislation towards improved indoor air quality. By understanding the challenges and opportunities faced by each group, it may be possible to develop more effective strategies for reducing radon exposure and achieving compliance with legal limits.

1.2 Method

A multi method approach was used to obtain data from each of the key stakeholders. Ethical approval for this study in Ireland and the UK was obtained from Trinity College, Dublin (SPREC092021-04), and for the focus groups in Belgium and Slovenia ethical approval was obtained through the University of Antwerp (no. SHW_21_135).

TABLE 1.1 Relevant indicators for radon mitigation in Belgium, Ireland, Slovenia and the United Kingdom.

	Belgium	Ireland	Slovenia	United Kingdom
Estimated lung cancer deaths due to radon per year (country population)	440 (11.6 million inhabitants) ^a	350 (5 million inhabitants) ^b	60 (2 million inhabitants) ^c	1,100 (6,733 million inhabitants) ^d
Reference levels for dwellings	300 Bq/m ³	200 Bq/m ³	300 Bq/m ³	200 Bq/m ³
Supporting levels for dwellings	Target level of 100 Bq/m ³ intervention level of 600 Bq/m ³	—	—	Target level of 100 Bq/m ³
Level of radon awareness among residents in radon risk areas (%) ^d	75% (<i>N</i> = 300)	59% (<i>N</i> = 1,003 in the entire territory)	75% (<i>N</i> = 453)	—
Objectives of mitigation in the national radon action plan	Mitigate all buildings with a radon concentration above and around the reference level (approx. 36,000 dwellings affected)	Mitigation rate increased to 30% for all homes over the reference level where financial support is available to householders by 2024. At present mitigation rate is about 20%	There is no overview of number of dwellings needed to be mitigated; nor is any estimate of need available	—
Advice on radon protection in building code	Yes (regional competence). The regional construction code of the radon priority area imposes the description of the radon protective measures by the responsible architect in the building permit	All dwellings built after 1998 in high radon areas must be fitted with radon preventive measures, namely a radon membrane and a standby radon sump. The standby sump can be activated if high radon concentrations are found in the building	Yes (guideline for construction of radon safe new buildings)	Building regulations require that buildings in certain areas should be constructed with protective measures that aim to prevent radon ingress
Registration of radon mitigation contractors	Registration is based on following a specific training on radon and being active in the radon field. Invited to repeat the training course every year, but not obligatory	Registration consists of participating successfully in a radon remediation course, tax compliance and public liability insurance. To maintain registration, the contractor has to	No registration is established yet	No particular licensing for radon mitigators is in place (only a building contractor licensed for electrical work). There are courses available by different organisations but no need to be accredited

	Belgium	Ireland	Slovenia	United Kingdom
		report annually anonymised data in relation to the provision of radon remediation services to EPA		
Information on available mitigation contractors	Published at responsible authority's website	Published on responsible authority's website	Not available on official website	Radon Council and the UK Radon Association publish lists of contractors provided by their members
Requirements on conveyancing	—	Three questions on radon testing are included in the conveyancing process that alert the prospective buyer to the risk of radon	—	During the house buying and selling process, radon is included in the conveyancing process through the local authority search and property information form completed by the seller
Links to indoor air quality (IAQ) programmes	In some cases, radon is included in the indoor air quality measurements	The UNVEIL project aims to understand ventilation and radon in energy efficient buildings ¹	Radon included in indoor air quality measurements when energy-saving interventions such as energy renovations and window replacements are carried out	There is regular interaction and cross-fertilisation of ideas between organisations working on radon and those engaged in air quality. Trainings are connected with trainings on indoor air quality by the Chartered Institution of Building Services Engineers (CIBSE) and other professional organisations. Radon is part of the indoor air quality programme: legislation on ventilation has been updated https://www.gov.uk/government/publications/building-regulations-approved-documents-

	Belgium	Ireland	Slovenia	United Kingdom
Links to energy saving programmes	—	Radon is a recommendation included in building energy rating reports for home energy performance	It is advised to measure during energy saving interventions but not required	I-f-and-overheating-consultation-version Large survey looking into radon concentrations in houses in 1990s and recently investigating energy saving measures put in houses demonstrate that radon concentrations have gone up. In the near future, radon is expected to become part of energy saving programmes
Average estimated costs of mitigation of a standard dwelling	500–5,000 €	1,000 € financial support for older adult people (over 65) for remediation is available—there are a range of criteria to be met in order to qualify which are not specific for radon. Additional actions for a financial support are on-going	1,000–10,000 €	£800–£2,000, and £5,000 if it is a complicated remediation. In case of low incomes, support is provided in the form of local authorities' grants

„Data from FANC website in 2016 (7% of lung cancer due to radon). <https://afcn.fgov.be/fr/dossiers/radon-et-radioactivite-dans-votre-habitation/radon/quel-est-le-risque-pour-votre-sante>.

„EPA Ireland. (2022). Radon in homes. <https://www.epa.ie/publications/monitoring--assessment/radon/EPARadonHome2022.pdf>.

„Birk M, Žagar, T, Tomšič S, Lokar, K, Mihor A, Bric, N, Mlakar M, and Zadnik V (2022). Impact of radon on lung cancer incidence in Slovenia. *Onkologija*. 26. 16–21. <https://doi.org/10.25670/oi2022-008on>.

„Public Health England. (2018). UK National Radon Action Plan. PHE-CRCE-043.

„The question was included in a representative public opinion survey in the three countries analysed in 2023 as part of the RadoNorm European project. The formulation of the question was: “do you know anything about radon?” and the answer categories included: “no,” “I have heard something about it” and “yes.” The percentage considered under the “level of radon awareness among residents” includes the answers “I have heard something about it” and “yes.” Source: RadoNorm pilot study report from public opinion survey Belgium 2020 2021. Development of a modular questionnaire for investigating societal aspects of radon and NORM. Doi: 10.20348/STOREDB/1174/1251.

„McGrath JA and Byrne MA. (2015). UNVEIL: Understanding Ventilatio and radon in energy efficient buildings in Ireland. EPA research report by National University of Ireland Galway. https://www.epa.ie/publications/research/environment--health/Research_Report_273.pdf.

1.2.1 Responsible authorities' perspectives

The study “Review and evaluation of national radon action plans established in EU Member States according to the requirements in Council Directive 2013/59/Euratom” investigated, among other aspects, the authorities' perspectives on barriers and facilitators for radon mitigation. A mixed method approach was used, comprising an on-line survey, content analysis of legal documents, group interviews, four regional workshops and the final workshop. The study was conducted in 27 EU MS and the UK. Firstly, the on-line survey allowed the authors to identify responsible authorities for different aspects of radon management including radon mitigation. Secondly, for the legal document review and content analysis, the authors collected RAPs or related legal documents if RAPs were not yet developed.

A protocol for the analysis guided the extraction of data to be analysed. Coders received specific training to ensure that the same method was used when analysing the data. The mitigation aspects were coded by two independent coders. In case of different data extracted and different codes, the third (master) coder discussed the differences and decided on the final data extracted (agreed data). Thirdly, the findings from the legal document content analysis were discussed with representatives in each country through group interviews. These group interviews (between 2 and 15 people) were conducted to validate the information as well as to respond on and clarify any missing information related to mitigation. The guiding questions for the interviews included: “Does the RAP define or include information regarding a strategy for post construction mitigation?”; “Which are procedures facilitating mitigations?”; “Has the EU MS (or the UK) implemented existing policy/policies for facilitating mitigations?”; “Are there any existing methods and tools (e.g., building code) for facilitating mitigations?”; and “Are there considered any indicators to measure the effectiveness of mitigations?” Notes from the interviews were sent back to all representatives for verification and additional feedback. Group interviews were conducted on-line between October 2021 and March 2022. In addition, four regional workshops were held to examine similarities and differences in mitigation actions, barriers and facilitators for mitigation of dwellings. The main focal points at the workshops included: (a) How can authorities ensure a significant difference in radon exposure through mitigation? and (b) How to motivate industry to offer mitigation services? The four workshops were conducted between October 2021 and March 2022. Finally, the overall results were discussed, verified, and compared at a workshop in Brussels, Belgium, with 50 participants from various countries in September 2022. The workshop covered topics such as procedures for facilitating mitigations, support for mitigation, guidelines for mitigation, and challenges related to mitigation and approaches to overcome them. For this paper, the general findings of the study have been substantiated with the specific findings in Belgium, Ireland, Slovenia and the UK.

1.2.2 Mitigation industry (contractor’s) perspectives

A protocol for semi-structured interviews was derived from existing research evidence on radon, as well as self-determination theory (SDT) (36) and entrepreneurship. SDT was used as a guiding framework to design the protocol for eliciting views regarding company history, level of mitigation work carried out, motivation, advertising and customer contact.

Interviewees were drawn from the Environmental Protection Agency (EPA) of Ireland and UK Radon Association (UKRA) lists of registered contractors. We selected Ireland and the UK as both countries have well-established regulatory oversight of radon mitigation and have dedicated radon agencies to provide easily accessible lists of contractors to members of the public seeking remediation. From a total of 25 contractors listed, 5 did not offer domestic radon mitigation services and were excluded. Of the remaining 20, 6 ($n = 3$ Irish and $n = 3$ UK) contractors agreed to interview who currently deliver domestic radon mitigation services. Six refused to interview, and 9 did not return calls.

Potential interviewees were initially contacted by email and follow-up telephone call. All participants were advised that interviews were confidential and their rights under General Data Protection Regulation (GDPR) were explained, and reporting would safeguard anonymity. Verbal consent was requested at the start of the interviews, which took place between October 2022 and January 2023. Semi-structured interviews were recorded remotely using MS Teams. Transcriptions were generated automatically and edited manually to improve readability. NVivo was used for content and thematic analysis (37).

1.2.3 Residents’ perspectives

Data for gathering residents’ perspectives were collected from focus groups comprised of individuals living in dwellings with radon levels exceeding the national reference level in Belgium, Ireland and

Slovenia. These focus groups were conducted in radon-priority areas in the three countries, which share similar radon risks but differ in their approach to radon risk communication. Table 1.1 outlines the key features of the selected countries in terms of radon, legal regulations and mitigation service provision. All three countries have strategies in place for raising awareness about radon, but these strategies vary. In Belgium, awareness is primarily raised through limited use of social media and press articles, and the effectiveness of these campaigns is evaluated to some extent. In Slovenia, the focus is more on providing personal advice and responding to radon-related questions, but the effectiveness of radon awareness campaigns is not evaluated. In contrast, Ireland has an evidence-based, theory-based and strategic approach to radon risk communication and supports citizen science projects related to radon testing and mitigation. The countries were selected as the differences reflect the variation that exists across the EU and will provide insight into commonly experienced barriers for mitigation across different contexts, as well as allowing for unique national experiences to be considered.

For the focus group analysis, each of the focus groups' discussion was transcribed and thematic analysis was applied (38). Transcripts were reviewed in detail for familiarity and accuracy before coding. Initial coding was performed in NVivo through multiple readings of the transcript. Following review of the codes, data were coded as barriers or facilitators of mitigation. Each focus group was initially coded separately, then combined for the final analysis.

Belgium

Two focus groups were conducted in the context of a broader study "Co-Designing Communication: A Design Thinking Approach Applied to *Radon Health Communication*," in which the focus was on discovering barriers and facilitators of mitigation behaviour (39). Participants in these focus groups had tested their homes and were recruited for this study through local authorities. The Belgian focus groups ($n = 5$) took place in March 2022 and were held online due to COVID-restrictions in place at the time. Both focus groups lasted around 2 h each. In the first part of the focus groups, barriers were identified that participants experienced throughout their mitigating process. Participants were encouraged to identify as many issues that they had experienced as they could think of, which were subsequently discussed in the group. In the second part of the focus groups, participants evaluated all the barriers and voted for those they found most important.

Ireland

Two on-line focus groups were conducted in January–February, 2022. The first group consisted of six people who did not mitigate their dwelling while the second group consisted of four participants who had mitigated. All participants received indoor radon test levels above 200 Bq/m³ and are from high radon priority areas. Most participants were homeowners, and only one participant rented their accommodation. Participants were recruited through the Environmental Protection Agency Ireland (EPA). Each focus group had a brief introduction, followed by a series of open-ended questions related to perceived barriers and facilitators to indoor radon mitigation. Participants reviewed the key barriers and facilitators and were asked for their perspective on which barriers or facilitators had the greatest impact on indoor radon mitigation.

Slovenia

Similar to Belgium, two focus groups were conducted in the context of the broader study "Co-Designing Communication: A Design Thinking Approach Applied to *Radon Health Communication*." Participants had tested their homes and were recruited through local authorities. The Slovenian focus group ($n = 9$) took place in May 2022 and was held face-to-face. Both focus groups lasted around 2 h each and followed the same protocol as the Belgian focus groups.

1.3 Results

Results are presented by stakeholder group, discussing the main barriers and facilitators for each group.

1.3.1 Authorities' perspective

The key issues raised relate to the legal (requirements for mitigation) and policy (e.g., the connection with indoor air quality and energy saving programmes) issues, communication and awareness campaigns, and the mitigation process (the cost and availability of financial support for mitigation, accreditation of radon mitigation contractors; education and training, and guidelines/instructions on corrective actions).

Legal requirements to mitigate dwellings with an exceeded radon concentration

In the countries analysed, the mitigation of private dwellings is not legally required but only advised. The lack of a legal mandate requiring the owner of the residence to mitigate is a barrier for radon mitigation.

Connection with indoor air quality and energy saving programmes

National RAPs may be linked with related programmes, such as energy saving and indoor air quality (IAQ). However, in general there are no systematic links with these programmes. Firstly, there are many attempts to connect energy saving programmes with radon prevention programmes; however, these are not systematic. Secondly, links with IAQ programmes are rather scarce and weak. In Belgium, only in some cases radon is included in IAQ measurements. In Slovenia, IAQ should include radon concentrations when energy-saving interventions are performed on public buildings in radon priority areas. The advisory guidance for contractors and householders from the Sustainable Energy Authority of Ireland on more energy efficient homes includes radon. These connections are recognised as important facilitators for mitigation. There is a need to further explore the counter effects of implementing energy efficiency measures compared to the increasing exposure to radon. The UK authorities referred to studies that indicate that increasing the airtightness of English homes, without providing compensatory ventilation, would increase indoor radon concentrations by around 60%, resulting in 278 deaths per year (40, 41).

During the study to review RAPs, the authorities discussed how to consider radon in relevant corresponding programmes, particularly for energy saving and IAQ programmes. Despite the lack of human resources in authorities to promote these connections, the benefits of establishing links different authorities were recognised as facilitators. Contacting energy agencies dealing with energy efficiency to raise awareness of the counter effects of implementing energy efficiency measures compared to the increasing exposure to radon was proposed. Furthermore, the connection of radon programmes with energy saving programmes at European level, such as the European Green Deal, was regarded as a facilitator.

Communication and awareness campaigns

Authorities organise communication and awareness campaigns annually within radon-priority areas in order to inform citizens about the risk of the indoor air pollutant radon and to motivate citizens living in a dwelling with radon concentration above the reference level to undertake mitigation actions. A wide range of groups are targeted by these communication campaigns, for instance, trade unions, practitioners, family doctors and lung cancer specialists in Belgium; building professionals, owners, sellers, local authorities and health and safety professionals in Ireland; local decision-makers and the general public in Slovenia and solicitors, purchasers and the law society in the UK. However, the lack of evidence-based, strategic and theory-founded communication campaigns is another barrier for increasing mitigation.

Costs and financial support for mitigation

Mitigation may range from €500 to more than €5,000 for private dwellings. This expense is usually a burden for residents and the owners of dwellings. Financial support for mitigation is provided in Belgium by the regional government. In Ireland, financial support was provided in a high radon area in which free radon testing was offered in conjunction with a 50% grant toward necessary remedial work. The empirical research conducted in 2018 by the Environmental Protection Agency (EPA) Ireland showed a very low uptake of grants from the citizens (42). In the UK, the Health Security Agency maintains an ongoing programme of work to promote action on radon and encouraging remediation in homes, using resources from national government where these are available.

Availability of radon mitigation contractors

Representatives of authorities at the workshops see the prevailing low interest of the building sector in providing radon mitigation services as a significant barrier to increase mitigation rates. They identified a low profit caused by low interest in mitigation as the main reason for the lack of motivation to provide mitigation services, especially for private dwellings.

Accreditation of radon mitigation contractors

Although accreditation or license for mitigation can facilitate the uptake of mitigation, the reality is that accreditations or licenses for mitigation are not issued in the majority of the EU MS countries. An exception is Ireland, where radon mitigation contractors are registered by authorities. For this, the contractor has to participate in radon mitigation training, prove tax compliance and provide liability insurance. The contractor has to report annually anonymised information on how many, where and what type of mitigation has been done. In return, a list of registered contractors for mitigation works is published on the internet site of the Irish authorities. In Belgium, remediators are advised to take a training course and are invited to repeat the training course every year, but they are not obliged. The Belgian authorities publish a list of contractors for mitigation of dwellings on their internet pages, but they do not guarantee the quality of the mitigation conducted by those contractors.

Education and training

Training courses, seminars or lectures for building professionals and workers in the building industry are or will be organised in most countries. A certificate of attendance is usually provided and, in a few cases, an accreditation. In Belgium, for instance, the local union of architects and the Belgian Building Research Institute organise a compulsory one-day training on radon with credits for architecture students. In Ireland, radon remediation and prevention courses were developed in the past until 2016 in collaboration with the construction and the radon industry and will resume in 2023. The national RAP in Ireland calls to work in partnership with the relevant professional bodies to develop a continuing professional development module on radon. In the UK, training courses on radon mitigation are also available for interested contractors.

Guidelines and instructions on corrective actions

Some countries, like Belgium, focus their mitigation efforts on developing and publishing technical guidance on mitigation. Although the guidelines provide information on technical solutions to the house owners if high radon levels are found, the guidelines are country-specific for the prevailing national building and geological conditions. Therefore, most of the countries still need to develop their own evidence-based guidelines. In Ireland, as part of the RadoNorm project, the EPA, Wexford libraries and the Healthy Wexford group have been working with citizen scientists within the Wexford community who have found levels of radon in their homes above the reference level of 200 Bq/m³ and have not yet remediated to reduce their levels. For this, citizen scientists have helped co-design and test a “*Do it yourself*” (DIY) kit for mitigation together with EPA and a radon remediation contractor.

1.3.2 Mitigation industry (contractor's) perspectives

Little is known about contractors' experience of running a radon mitigation business. In the following sections we present evidence for how contractors start and maintain a business, manage advertising, required competencies and facilitate homeowner engagement.

Getting started in the service

Two aspects appeared important to setting up services to provide radon mitigation to homes. One route to service provision arose from having existing business in radon and enough work, such as in a large government contract to justify the move into domestic radon mitigation. This route into radon contracting generally started with response to tender for schools, social housing or hospital contracts. A second route into service provision came from those who were working in existing companies where radon contracting was already present and who decided to leave to start their own radon mitigation services

"I was providing concrete cutting services. So I have diamond tip the drills for, you know, drilling large holes... it was at the time that the government was doing the mitigation work in the schools. There's money to be made and we had the men, we had the equipment." Interviewee 3.

Viability of radon mitigation services

A minimum viable business needs to have repeatable sales and momentum, which can be interpreted as actual or predicted turnover. None of the interviewees believed that a radon mitigation-only business was viable.

The contractors interviewed appeared to suggest that they normally completed 1 to 3 jobs per month for a local or regional company, and a maximum of 8 for a national company using subcontractors. All interviewees stated it was currently not possible to run a domestic radon mitigation only business but that it would normally be a minor part of their main business.

"There is no recurring business in the radon industry at the moment... so nobody in their right mind is gonna set up a company and assign overheads to it... when you just don't know you're gonna get the business... the only possibility where there's a possibility of business happening is through contracted business... say social housing ... where you can become part of reactive and planned maintenance of existing property stock." Interviewee 2.

The sales conversion rate is quite poor, which further undermines the viability of the business.

"I would say for the general public our efforts are pretty poorly responded to. Everyone is seems so interested and everyone seems so grateful at that point of getting information out of you, to the point where even potentially purchasing a test kit. But the actual return, or the conversion of a high reading into mitigation is probably quite low." Interviewee 1.

Despite the campaigns raising radon awareness, demand for radon mitigation for some contractors has been consistently low for almost a decade.

"...we probably do three or four jobs a month... after eight years... we've seen no real increase." Interviewee 1.

Given the low level of demand, one contractor stated that it was, *"...not learning how to install radon fans...(but) learn how to run a business and make it business viable in the very small segment of market."* Interviewee 2.

Homeowners are reluctant to mitigate because of *"Cost, pure and simple"* Interviewee 4. but those who are likely to mitigate are, *"...people that have a disposable income,"* Interviewee 6.

Based on the above challenges, one contractor who refused to grant an interview had already left the radon business as there were not enough domestic jobs to justify continuing.

Advertising radon mitigation services

Given the issues noted with gaining customers, it was noteworthy that contractors typically do not advertise as the costs are not viable compared to the market reach: the customer base tends to be regional or even national. While some contractors will engage in awareness campaigns, they are dependent on mass media campaigns run by government or trade bodies such as the EPA in Ireland or UKRA.

"If it's not happening, I can't make it happen, right? I'm completely reliant on others (mass communicators) to create a need for it." Interviewee 3.

Contractors maintain visibility to the public through being on national (e.g., EPA/UKRA) register, using Google Ads, and having their own web pages to provide information. None of the contractors used radio advertisements or flyers:

"... maybe 9 or 10 years ago we put ... flyers ... into all the papers and the post office ... the feedback wasn't huge ... we spent a bit of money in that ... I have boxes of these brochures still out there anyway, I'd be slow to do that again." Interviewee 4.

Only one company actively used social media and blogs and previously hired a public relations company to manage social media for them.

Purchasing local advertising is only worth it if enough sales can be generated to cover the advertising costs and return a profit. Homeowners were reported to be more motivated to test after regional/national advertising and therefore look for contractors locally. However, one contractor highlighted that Google Ads are very "congested" now and may not be worth it as, *"spending absolute premium money just to get your ads on the first page does not make any sense you know because of the margins."* In addition, when competing companies appear in a search the *"customer cannot discriminate between an expert and non-expert."* Interviewee 2.

Motivation to provide services

Some contractors described their motivation to provide radon mitigation in terms of the health benefits, although the need for the service to be commercially viable was emphasised.

"I just think about it from the health of just general health of people... we want our families to be healthy." Interviewee 2

"I'd always go moral over financial to be fair, within reason... (but) I'm still a businessman." Interviewee 4.

Regulation

Contractors noted that the building regulations for ventilation and radon are not well known: *"...building regulations for ventilation are based on minimum standards...there is so much ignorance actually in the trade relating to this... most installers out there do not know the regulations to the level that they should do for ventilation..."* Interviewee 2.

"...I can even speak to health and safety people in this area who were like 'radon what's radon?'" Interviewee 1.

One contractor (Interviewee 2) highlighted the problems caused by the failure to install ventilation equipment correctly *"I walk into properties and see they have been...not installed physically correctly, so they have used the wrong duct"* and *"we see more often than not...the electrical compliance side of*

those installations, people putting them in with on off switches.... because people turn them off and then and then suddenly there's no ventilation."

1.3.3 Residents' perspectives

The barriers and facilitators identified by the residents can be categorised into four broad categories: individual factors (risk perception, knowledge of how to mitigate and cost), inter-individual factors (trust), organisational factors (access to mitigation services) and governmental factors. It should be noted that some issues transcend these categories but are described here under these headings for simplicity of presentation.

Individual factors

a) Risk perception

Residents who mitigated their dwellings in Ireland perceived radon as a high risk: the threat may affect them or their family members, especially children, which may have negative health consequences:

"we have children as well, which we want to protect. So that's why we went we better get it done." (IRE)

In contrast, non-mitigators noted that lung cancer is a complex issue, which cannot be explained solely by radon.

not convinced about the dangers of it (radon). I don't think I've ever come across anybody with lung cancer as a result of radon." (IRE)

The importance of communicating the level of risk in a way that motivates individuals was noted across groups:

"(risk communication)... I think it's important ... The authorities and the companies don't show this sense of urgency." (BEL)

"To inform and make people aware about radon risks." (SLOV)

b) Knowledge of how to mitigate

A barrier to remediation arises from the lack of information on how to proceed:

"Would need to know what to do step-by-step after receiving the measurement result. Who can help me?." (SLOV)

"They do tests, but they're long term tests and it, it uh, it gives you the average in the house but it doesn't help to know how to fix the problem and where the real leaks are and stuff like that which is imperative to actually fix the problem." (BEL)

An interesting experience from one of the participants in Slovenia was shared during the focus group. The participant followed the mitigation guidelines published on the authorities' internet page. The mitigation was not efficient since the radon was "pushed" from the ground floor to the highest floor (2,733 Bq/m³).

c) Cost

Mitigation costs and costs for maintenance/running costs of mitigation were perceived as high by those in Ireland who did not mitigate.

"A constant input of funds regarding ah to keep it (fan) running. And if you don't do that or maintain it or the fan breaks down, you're back to square one and you're back to facing another cost to try and resolve the issue." (IRE)

The issue of cost arose in the focus groups in other countries too; therefore, in order to facilitate greater levels of mitigation the costs should be affordable.

"That costs related to remediation would not be too high." (SLOV)

"It would be interesting to perhaps make the information accessible to people by telling them, um, it's perhaps not so difficult to remediate, nor so expensive." (BEL)

Some countries provide subventions to help home-dwellers and these financial supports can help overcome barriers associated with financial capacity to pay for the mitigation work. Being able to access such funding is a critical facilitator.

"The council...paid practically all of it." (IRE)

1.3.4 Inter-individual factors

Trust

Knowledge of the mitigation process will not translate into action if there is a lack of trust with the mitigation services. Non-mitigators have lower trust in the radon related information shared by authorities and contractors than mitigators.

"... they had a vested interest maybe in selling radon barriers or something like that." (IRE)

In order to overcome the potential lack of trust, the integrity and independence of the information and service should be emphasised.

"It will be someone who has both knowledge and expertise but who, ideally, is not necessarily a salesman from a company." (BEL)

"... some people will have an issue with regards to a government agency recommending things to get done and people will be concerned...do they have a genuine reason behind that or are we just trying to meet certain targets to make the country look good?" (IRE)

In addition, a facilitator of mitigation is that the home dweller can trust the quality of the work performed to reduce radon levels in the home.

"Because if I'm going to do something that's going to cost me money, time, take steps, but if I'm not sure it's going to be effective, ...I'm going to drop it." (BEL)

"That somebody would guarantee for quality of the remediation work." (SLOV)

Using personal testimonials and mass media to communicate the positive experiences of remediation, especially amongst those living in the same community, would facilitate greater trust and would encourage individuals to seek such services.

"Personal testimonies of people during remediation." (SLOV)

"More information on successful remediation and re-tests in mass media." (SLOV)

1.3.5 Organisational factors

Access to mitigation services

Once a high level of radon has been detected, it is essential that information is provided to the home dwellers on accessing the mitigation services.

“Would need to know what to do step-by-step after receiving the measurement result. Who can help me?” (SLOV)

In addition, having access to a sufficient number of appropriate mitigation services will facilitate increased level of mitigation for those with high levels of radon.

“To have more remediation services available.” (SLOV)

“Well, we have, we just have our vision but, to give you an example, we have a list of companies in Luxembourg that should be able to deal with radon. We have contacted them all, the whole list, there is nobody who really has experience on it, but it's on the list of experts. So, to make it work, to make people apply solutions, companies that are, uh, led to be professionals and experts that are not and they say it themselves that they are not. It's a bit difficult.” (BEL)

Governmental/legal authority factors

The role of legal authorities (e.g., national governmental, state /regional councils, etc) was noted in all focus groups. There was a general sense that as radon is a key health issue, the legal authorities should be more involved in pro-actively addressing radon; it should not be left to the individual.

“If radon is a problem, then state should pay for tests and remediation.” (IRE)

“Will (would) the state co-finance the remediation?” (SLOV)

In Ireland and Belgium, those who mitigated suggested that the State should make radon mitigation compulsory, including radon in all relevant building legislation.

“Central policy from government should have some carrots in it to entice people from all incomes to address a radon problem in their house, whether it be financial support, whether it be provision of a monitor, whether it be a certificate for your house before you sell it that it is radon free. Unless it's highlighted from central government as a policy, people will not buy into it.” (IRE)

“I think it's essential that there is a law that obliges, especially in new buildings, that there is an avoidance of radon risks by specific measures to be taken and that are verified by standardised tests or certified that it's correct.” (BEL)

1.3.6 Integrated approach

The above sections have noted that barriers exist at individual, inter-individual, community, organisational and governmental levels. Many of the issues cut across these levels. Participants noted the fragmented nature of the mitigation process and appealed for an integrated approach from all stakeholders; such an approach would facilitate increased radon mitigation.

“All experts need to work together and they need to communicate and increase awareness about measurements, remediation, general information about radon, about the process including about potential subventions.” (SLOV)

1.4 Discussion

The present study examined the perspectives of key stakeholders on the barriers and facilitators to the mitigation of the air pollutant radon. The key aspects identified by each stakeholder group are outlined separately before considering the novel insights that emerged by taking a multi-stakeholder lens.

The first facilitator, as recognised by the authorities, is a legal requirement for mitigation of private dwellings in case of exceeded levels of radon indoor as already highlighted previously (3). Generally, owners of public buildings with an exceeded radon concentration are legally obliged to mitigate the building, but in the case of private dwellings, mitigation is only advised. The second facilitator is evidence-based, and strategic communication and awareness campaigns, which are organised by authorities to motivate for behaviour change (testing and mitigation). The lack of such communication campaigns has been recognised by the Potsdam radon communication manifesto (16). Target groups for these campaigns vary among countries; however, they should be more targeted (17). Although increasing awareness is necessary, it is not by itself sufficient to result in radon mitigation (23). The third facilitator is available financial support for residents to mitigate and simple processes to obtain the available grants. Although this finding confirms previous research (43), it should be noted that some countries provide financial support but there is a low uptake of available resources, including in one of the investigated countries (Ireland). The fourth facilitator is the connection with indoor air quality and energy saving programmes, which are currently not systematically linked. The lack of connection between radon risk management and other relevant policies was highlighted previously as a barrier to mitigation (20). The authorities discussed how to consider radon in these programmes and the benefits of establishing links between different authorities for instance public health, spatial planning and nuclear safety authorities. Another facilitator is the accreditation or licence of radon mitigation contractors, which is not yet widely implemented. In the present paper accreditation and licensing is understood in the broadest sense of meaning any form of indication that the company has purposefully increased its competence in the field of radon mitigation measures, in particular by attending official courses, e.g., those organised by the regulatory authority. Authorities suggest that the main reason for the lack of motivation to become a radon mitigator is low profit, especially in the case of private dwellings. Given the perspective of the authorities regarding radon mitigation contractors motivation, a key strength of this paper is that we obtained data from contractors on their experiences of being in the radon mitigation industry.

To the best of our knowledge, this is the first study to examine radon mitigation from the perspective of the mitigation industry. Of interest, currently running a domestic home mitigation-only business is not feasible due to the low turnover of mitigation jobs. Consequently, all participants offered domestic mitigation work alongside other sales and services such as ventilation, conservation, commercial radon work or radon test sales, with mitigation as a minor service. Similar to the authorities' perspective, the importance of awareness campaigns was noted by contractors: homeowners tend to respond to mass media campaigns and not *ad hoc* local advertising. Consequently, increasing the frequency of media campaigns and giving contractors prior notice to optimise their public relations strategies might produce higher mitigation rates.

Contractors typically do not advertise as the costs are high with poor sales conversion rates. Local advertising rates are high and only worth committing to if enough sales can be generated to cover the advertising costs and return a profit. None of the contractors used radio advertisements or flyers in recent years due to low response rates. Contractors suggested that homeowners found them during conveyancing, through either an online radon register or via an internet search. Membership of a professional register and having a good website are important. Cost also emerged as a facilitator for mitigation. As homeowners want to pay low costs for building work, contractors may choose the cheapest solution where minimum standards are specified.

Radon was associated with ventilation but the minimum standards for ventilation are often poorly understood by other professionals in decision-making roles. Those interviewed differentiated themselves from other tradespeople on their in-depth knowledge of the building regulations and the need for problem-solving for individual mitigation cases. As noted in the results, the experience of the resident who followed published radon mitigation guidance highlights the potential for inadequate ventilation solutions to inadvertently exacerbate the health risks of radon. This has implications for both improvements to regulations and training of radon mitigation installers. Support for this view is that recent current building regulations in the UK have been criticised for not being “fit for purpose” and poorly applied (44) and that radon-risk is further predicted to increase with different building designs, insulation, and air conditioning systems due to the impact of climate change (45, 46). This finding reflects the point made by the authorities regarding the value of integrating radon with energy saving programmes.

Lastly, this research looked at the perspective of residents concerning barriers and facilitators. Concerning the individual factors, risk perception varied among mitigators and non-mitigators, showing that risk perception can influence mitigation decisions, depending on a sense of urgency, personal relevance or even engagement with the health issue at stake. However, it should be noted that other research has not found a relationship between risk perception and mitigation; for example, people living in high radon affected areas find the risks of radon acceptable, despite being more concerned about these risks (47, 48). The question remains as to what variables differentiate those who mitigate from those who do not mitigate. One possible explanation of this discrepancy could be the health value and locus of control of the residents regarding radon. Residents with an internal locus of control might believe that they themselves have control over their health and therefore are more likely to take action, whereas residents with an external locus of control might believe their health is in the hands of others, or chance, and might avoid action (49). This could also be related to costs, as those who did not mitigate indicated that the burden of high costs was a barrier for mitigation.

When considering the inter-individual factors, trust is perceived as an important barrier to mitigate. Trust is related to the intentions of those who communicate about radon mitigations, but also about self-efficacy (confidence) of the residents to get the mitigation performed, and their perceptions of successful efficacy of the mitigation. The focus groups show that on the one hand side, guaranteeing results would increase their perceptions of its success, and on the other hand side, seeing testimonials of those who performed mitigation, would increase the homeowners’ self-efficacy to get the mitigation performed. Previous research showed that self-efficacy is a predictor of radon mitigation (50), which can be increased by modelling the behaviour through testimonials (51–53). The main facilitator in this regard would be to increase trust in the mitigators, the residents themselves, and the solution as an effective way to decrease radon levels in their homes.

Regarding the organisational factors, residents identified the need for clear information on the needed steps to mitigation, and on where to find the right services to facilitate this mitigation. This ties in with the barriers explained at the level of the mitigation industry, where the lack of viability of radon mitigation services is emphasised. A similar trend is visible when looking at the governmental factors, where the residents would prefer to see more government urgency and legislation regarding radon measures, however, only a minority of countries have these kinds of legislations in place. This summarises into the need for an integrated approach, highlighted by the residents, where all stakeholders should convey the same message, and support this message with appropriate action. Such an integrated approach would facilitate radon mitigation behaviour.

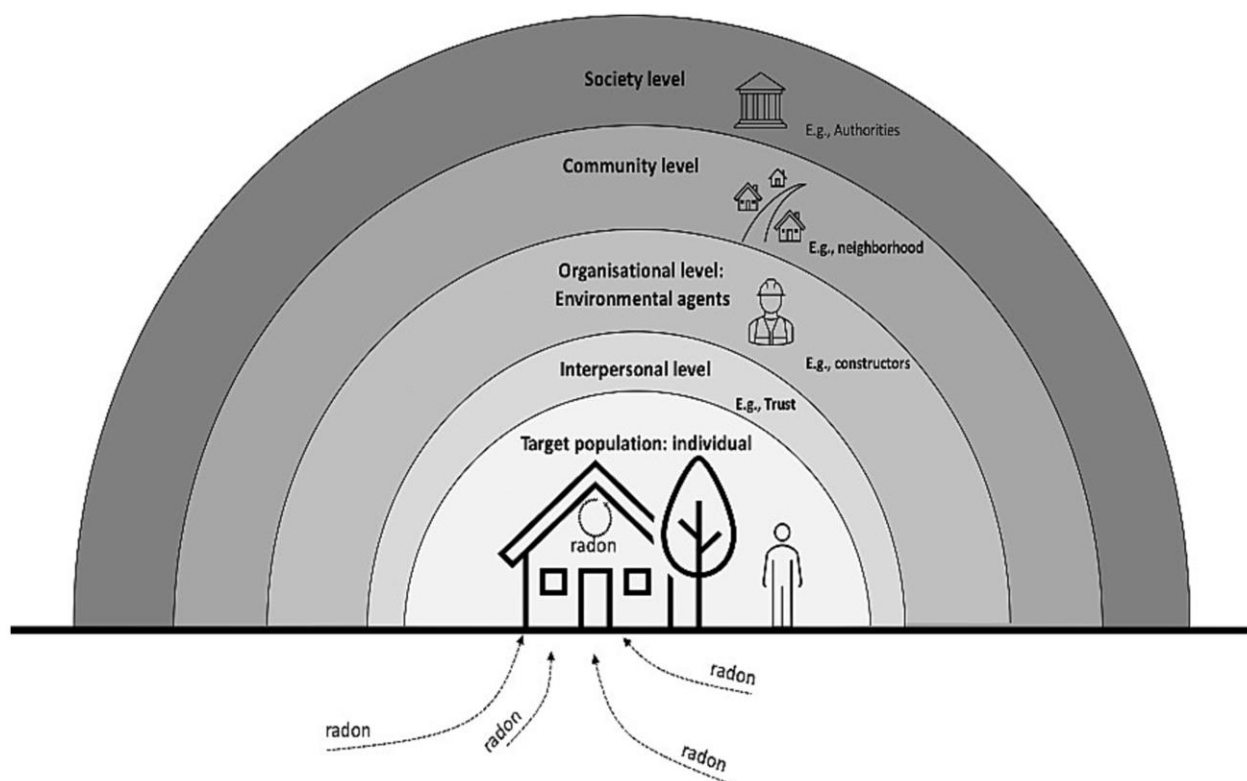
Figure 1.1 illustrates the value of the psycho-social-environmental lens in helping understand the complexity of radon mitigation. Radon seeps into domestic dwellings and can permeate all levels of the dwelling. In the absence of a legal requirement to mitigate, the individual must decide whether to mitigate

and this decision is influenced not just by the individuals' knowledge and perception of risk from radon but also the cost, availability and accessibility of contractors to perform the mitigation; however, individuals must have trust in the contractor's qualifications and motivations for conducting the work. Examples of others in the individual's community having mitigated also create trust in the need to mitigate and specific contractors. The present novel findings highlight the need to contextualise radon mitigation decision making in a complex system that requires facilitators to be present at multiple levels.

Based on the findings, Table 1.2 summarises the key radon mitigation facilitators identified by the stakeholders, the level(s) at which the facilitators operate, and the extent to which the facilitators are present. The absence of such facilitators creates a barrier to radon mitigation. The perception of the extent to which the facilitators exist in practice varies considerably and yet each contribute to the increased mitigation. Several facilitators were noted by all stakeholders: legal regulations/buildings code; evidence based and strategic awareness campaigns; accessible contractors, and affordable costs. In essence a campaign to make people aware of the health risks of radon is required, and for those with high levels of radon it must be easy to identify a trustworthy contractor and the cost should not be prohibitive. Financial support can be made available to support residents in undertaking the mitigation work. All of this needs to take place in the context of legal requirements to mitigate dwellings with an exceeded radon concentration, with clear policies connecting radon as an indoor pollutant with indoor air quality and energy saving programmes.

The present findings highlight that radon risk management is a complex "Wicked" problem; such problems are complex policy challenges that require a coordinated, cross-government response and where there is no obvious solution (54). For example, all stakeholders highlighted the importance of campaigns to increase awareness of radon to risk perception; yet even when awareness is high and radon is perceived as a risk, mitigation rates are low (19, 23). In addition, although all stakeholders noted the need for financial support for radon mitigation, it should be noted that even where such supports are available, evidence indicates low levels of uptake. For example, free radon testing was offered in conjunction with a 50% grant towards necessary remedial work in a radon priority area in Ireland; however, only 20% took up this offer (42). Consequently, additional research is needed to understand why there is such a low uptake of the subventions, e.g., is it too difficult to access the subvention, it is not sufficient to meet the cost? The complexity of these issues means that, while the ultimate goal (e.g., radon mitigation) is clear, there is no obvious solution to achieve this goal. Rather, the solution may need to be arrived at incrementally from a psycho-social-environmental lens through an iterative process that involves stakeholders at all levels to create an integrated approach to radon mitigation. As noted, wicked environmental health problems are most likely to be addressed by the application of effective community health promotion skills, a sustained commitment to sound epidemiological science, the application of systems thinking, and transparent communication among all stakeholders (54). Communications about radon risk tend to be solely focused on awareness communications targeting the individual in radon priority areas to act; however, evidence indicates that, although necessary, these are not sufficient by themselves. Communication among all stakeholders requires clear, consistent and integrated communication and collaboration between all key radon responsible authorities.

Further research to examine the perspectives of residents and radon mitigation contractors in other countries is warranted. In addition, the perspectives of other key stakeholders (e.g., health care professionals, policy makers) across countries should be examined to further understand barriers and facilitators to radon mitigation.

**FIGURE 1.1**

The individual is nested within various levels that influence radon mitigation rates.

TABLE 1.2 Radon mitigation facilitators identified by stakeholders.

Facilitators for mitigation [stakeholder level: legal (L), organisational (O) or individual (I)]	Recognised by the stakeholders group	Do the facilitators exist in practice according to the stakeholder group's perception?
Legal requirements to mitigate dwellings with an exceeded radon concentration (L)	Authorities; residents	No; no
Building code (L)	Authorities; contractors; residents	Not sufficient; not sufficient; not sufficient
Evidence based and communication strategies focused on a behavioural change (L)	Authorities	Only in few countries
Awareness campaigns (L)	Authorities; contractors; residents	Yes; yes, but not continuous; yes
Connection with indoor air quality programmes (L)	Authorities	Not sufficient
Connection with energy saving programmes (L)	Authorities	Not sufficient: only in few countries
Accessible contractors (L, O, I)	Authorities; contractors; residents	Not sufficient; not sufficient; not sufficient
Sufficient demand for mitigation (O, I)	Contractors	Not sufficient
Affordable costs for mitigation (L, O, I)	Authorities; contractors; residents	No; no; no
Significant financial support for mitigation (L, O, I)	Authorities; residents	Only in few countries; only in few countries
Accreditation of radon mitigation contractors (L, O)	Authorities	Only in few countries
Education and training provided for contractors (L, O)	Authorities	Mainly yes
Trust in the mitigation process (I)	Residents	Not sufficient
Guidelines and instructions for mitigation available (L, O, I)	Authorities; residents	Yes; no
Risk perception (I)	Residents	Not sufficient

1.5 Conclusions

The article highlights that previous studies have only examined barriers to radon mitigation from the perspective of residents, but this study takes a more holistic approach by identifying psychological, social and environmental facilitators and barriers to radon mitigation in four different countries for residents, responsible authorities and mitigation industry. The findings demonstrate the complexity of the radon mitigation process and suggest that interventions aimed at increasing mitigation should target groups beyond just residents, such as constructors, health professionals, and policy makers. Effective interventions should also utilise different media to reach specific audiences, but communication alone may not be enough to change behaviours if there are no contractors available to advise and assist residents. The study concludes that an integrated approach from radon mitigation policy to provision is necessary to effectively lower levels of this indoor air pollutant.

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2. Understanding stakeholder uncertainties in environmental remediation: Lessons Industrial Legacy of Mixed Radioactive (NORM)-Chemical Contamination

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2.1 Introduction

It is estimated that out of the 2.5 million potentially contaminated sites with various pollutants across Europe, approximately 14% will require remediation (Cappuyns, 2016; EEA, 2019). Remediation is a socio-technical process fraught with uncertainties, directly affecting the sustainability of environmental, societal, and economic systems (Bardos, 2014). Uncertainties in the remediation process refer to situations where facts, data, or phenomena, along with their causes or consequences, are not known with certainty by decision-makers within their specific context (Guillevic et al., 2019). It is important to recognize that every stakeholder is also a decision-maker. Some make decisions on a personal level (e.g., whether to have a garden party on potentially polluted soil), while others make decisions that affect groups of people (e.g., determining who will bear the costs of the remediation process).

Despite the critical importance of recognising and addressing uncertainties in environmental remediation efforts, there remains a significant inconsistency in knowledge regarding the diverse nature of uncertainties experienced by stakeholders such as affected populations, remediation experts, authorities, industry and those reported in the mass media. This study aims to fill this gap by specifically focusing on uncertainties at sites contaminated by historical industrial practices involving naturally occurring radioactive materials (NORM).

NORM refers to radioactive substances that contain significant amounts of natural occurring radionuclides, such as uranium-238 (^{238}U), thorium-232 (^{232}Th) and their decay products, and potassium-40 (^{40}K) (Popic et al., 2023). The term also encompasses materials where the activity concentrations of these naturally occurring radionuclides may be enhanced due to human activities (IAEA, 2022), for instance industry. Examples of radiological by-products from industrial activities include cement production, oil and gas extraction, coal-fired power plants, phosphate fertiliser production, groundwater filtration, the radium industry, and uranium mining and milling. (Popic et al., 2023). NORM contaminated sites are areas where hazardous substances are found in the environment at concentrations higher than natural background levels, potentially posing risks to human health and ecosystems (EEA, 2021). To assess the number and status of NORM-contaminated sites in Europe, the RadoNorm project conducted a survey in 2022 involving various stakeholders, including regulators, industry representatives, and remediation experts. However, the survey encountered low response rates from the industry and waste management sectors, with authorities citing "confidentiality concerns" (Popic et al., 2023, p. 12). This indicates the high sensitivity of the topic for industry and authorities, highlighting potential uncertainties surrounding the management of NORM-contaminated sites. Due to its radiological properties—being undetectable by sight, smell, or touch—NORM sites may cause additional uncertainties, particularly for residents living near affected sites (Perko et al., 2017).

While remediation of a NORM contaminated site involves measures aimed at reducing radiation exposure from existing contamination, either by treating the contamination directly or blocking pathways

to human exposure (IAEA, 2016), its unequivocal benefits for human and ecosystem health have been questioned in recent decades (Cappuyns, 2016). Remedial actions have been found to (potentially) cause significant environmental, societal and economic impacts (O'Connor et al., 2019), showing the need to consider potential impacts on all these three dimensions when remedial options are discussed and evaluated (Church, 2001). The increased attention to sustainable environmental management in latest years reinforces this, by defining sustainable environmental remediation as *“a project that represents the best solution when considering environmental, societal and economic factors – as agreed by the [project] stakeholders”* (Bardos, 2014; NICOLE, 2010).

The notion of stakeholders, and of stakeholder engagement specifically, is seen as a crucial aspect of sustainable environmental remediation. Stakeholders are dynamically defined by various actors and are often categorized within pollution management by the quadruple helix model, which includes industry, government, civil society and academia (Elias et al., 2010). Several scholars have argued that the quadruple helix of stakeholders should be extended to N-Helix Models covering the political, education, economic, natural; and media-based and culture-based stakeholders (González-Martínez et al., 2025). The basis for this argumentation is the circulation of knowledge between the various systems and the capitals that are generated as a result of this circulation, as well as the internal growth of knowledge of each separate system (Carayannis et al., 2021). The inclusion of all these knowledge systems, and their integration in environmental management, is deemed to lead to more sustainable outcomes, as knowledge is less rigid and more adaptive to change (Folke, 2004). Integrating knowledge also allows for contextualisation and for a better understanding of behaviours, such that uncertainties arising, among others, from the intertwinement of societal and technical aspects can be reduced (Gray et al., 2012; NRC, 2008).

A recent systematic literature review by Turcanu et al. (2022) on societal studies related to NORM and radiologically contaminated sites has highlighted a range of societal challenges associated with the environmental remediation of historical contamination. However, the study emphasises that there is still a significant inconsistency in evidence-based research to fully understand the uncertainties faced by various stakeholders throughout the often decades-long stages of remediation projects, including aspects related to sustainability. Another study, based on a grey literature review, found that during remediation projects, a multitude of interconnected aspects come into play. These include technical considerations (e.g., feasibility, mixed chemical and radioactive pollution), legal factors (e.g., liability, regulatory gaps), environmental concerns, economic impacts, and societal dynamics (e.g., community values, participation or lack thereof), all laden with uncertainties (Guillevic et al. 2018). An additional aspect of complexity is the multitude of stakeholders, often with diverging concerns, motivations, and expectations (Perko et al., 2019).

It has been pointed out that although the few existing societal scientific studies offer some insights into this complexity from a societal lens, for instance regarding risk perception and risk communication or ethical issues (e.g. König et al, 2014; Oughton et al., 2013; Perko et al., 2019; Guillevic et al. 2018; Perko et al., 2019), the review of Turcanu et al. (2022) showed the importance of unpacking and including in decision-making processes considerations regarding perceptions of residents' own health or their children's health, distribution of costs for remediation, equity and justice, participation and preservation of community values. However, most of the societal challenges identified have not been addressed yet. In particular, there is a need to understand how members of affected communities make sense of the societal, environmental and economic uncertainties linked to long term radiological exposure situations (Guillevic et al., 2018; pp. 19). As highlighted by Hoti et al. (2020), existing studies on uncertainties predominantly analyse how they are conceptualised and managed by scientific actors or technical experts, while comparatively little attention has been paid to how citizens or other stakeholders perceive and experience uncertainties. Mass media serve as a primary source of information for the general public, functioning both as a communication tool for various stakeholders

and as society's "watchdog", especially in the radiological exposure scenario (Perko et al., 2012). At the same time, media outlets must address the financial demands of publishing or broadcasting, often influenced by the adage "bad news is good news," a common principle in journalism. The role of mass media has become increasingly significant as they contribute to the emergence, development, and resolution of crises (Perko et al., 2012). Previous research highlights conflicting interests regarding transparency in radiation risk communication among industry, regulators, action groups, and the public (Perko et al., 2020). The conflict revolves around the appropriate degree of transparency: from the position that "the public has the right to know," to the view that certain information must remain "privileged" to ensure the security of critical infrastructure, to the argument that information should be "restricted" to avoid misinterpretation or misuse. Additionally, concerns about transparency often extend to its potential impact on the market value of the responsible industry (Perko et al., 2012).

This study responds to the following research question:

(RQ): "How do stakeholders, including affected populations (residents), remediation experts, authorities, industry, and the mass media, perceive and experience uncertainties encountered during long-term environmental remediation processes at mixed chemical-radiological contaminated sites in Flanders, Belgium?"

The results of the study stimulate discourse on sustainability challenges and underscore the perspectives and apprehensions of distinct stakeholder groups engaged in or impacted by the remediation efforts.

2.2 Study background: Legal framework and contaminated sites

The Flemish Region, a densely populated area of Belgium with a population density of 504 inhabitants per square km and a total area of 13,522 square km, underwent significant industrialisation after World War II, including the development of industries that produced radium and phosphate. This led to significant soil pollution from both radionuclides and chemical industrial waste much before there was any regulation regarding NORM. Consequently, the region has many polluted sites. Between 1995 and 2014, authorities registered about 22,500 high-risk sites, which were investigated out of an estimated total of 76,000 potentially mainly chemically polluted sites (IAEA, 2014). Awareness of mixed chemical pollution, NORM, and pollution from the radium industry dates back to the 1960s, with the first comprehensive soil surveillance conducted in the 1970s (Kirschman et al., 1973). Systematic monitoring of radioactive and chemical pollution from the phosphate industry began only in the early 1990s, prompted by findings during the decommissioning of the phosphoric acid installation in Antwerp (Cottens, 1994). In 1994, the Belgian radiation protection authority (FANC) was established, with one of its primary tasks being the implementation of a systematic radiological soil surveillance program. This program ensures adherence to the ALARA approach (As Low As Reasonably Achievable) for minimising exposure to ionising radiation from human activities and natural sources (Sombré et al., 2004), prompting the need for remediation projects. To support this, in 1995, Belgium implemented one of the world's first soil decrees aimed at safeguarding property buyers through soil certification. This legislation enabled the mapping of potentially contaminated sites and distinguished between new and historical pollution, mandating polluters to promptly clean up newly identified contamination and "polluter pay" requirement. Historic pollution, often discovered during soil investigations, poses challenges as the responsibility for remediation often cannot be assigned to a specific polluter, since the original polluter may no longer exist.

Since the implementation of the General Regulation for Protection Against Ionizing Radiation in 2001, all NORM sites in Belgium are required to be regulated by authorities (Royal Decree of 20 July 2001). Industries with NORM disposal obligations must adhere to specific decommissioning requirements, including: (i) describing the installations to be cleaned up or dismantled, (ii) conducting radiological characterization of contaminated parts, (iii) proposing work protocols with operational protection measures for workers, (iv) detailing residues produced during decommissioning, (v) assessing disposal or treatment options for these residues, and (vi) planning the decommissioning operations (Pepin et al., 2016). More substantial updates and changes in national regulation were included later, by 2018, i.e. with respect to the official deadline for the transposition of the latest EU Basic Safety Standard directive requirements into national legislations (EC, 2013).

As of 2018, FANC reports approximately 20 NORM legacy sites across the country, with an additional 9 sites specifically designated for NORM disposal (Cinelli G et. al, 2018). These sites are primarily linked to the phosphate industry, involving phosphogypsum stacks and related discharges. Moreover, historical activities in radium and uranium production have also contributed to environmental contamination, necessitating significant remediation efforts. Our case studies focus on two specific sites within this context.

Both sites are situated in densely populated regions that have been centres of industrial activity since the nineteenth century, involving numerous stakeholders. As of our study period, active industries continue to operate at both sites, providing employment opportunities for local communities.

The first site is characterised by historical pollution from metal processing and the radium industry, resulting in substantial radioactive contamination both within the factory premises and its surroundings. This contamination has affected nearby dumping sites, the banks of a neighbouring river, and several streets in the adjacent town. Managing this pollution and decisions related to remediation have required complex negotiations among citizens, industries, local governments, environmental groups, and the media (IAEA, 2014). Extensive stakeholder involvement, including working groups, public meetings, and participatory decision-making on remediation strategies, has been ongoing. While significant progress has been achieved in remediation efforts during our study period, challenges persist regarding the clean-up of dumping sites.

The second site is associated with historical pollution from the phosphate industry, where contamination spread extensively downstream in the river from the factory. This situation necessitated the largest watercourse remediation operation ever conducted in Belgium. Complicating matters, the operator went bankrupt in 2009, abruptly halting activities related to remediation. Subsequently, the site was divided among multiple owners, each responsible for different portions of the real estate and production equipment. Resolving liability issues among these parties was protracted and required substantial negotiation. Environmental remediation efforts for both chemical and radiological contamination were underway at the time of our study and continue to progress as of the current writing.

We note here that from a regulatory point of view a distinction is made between NORM industries, such as the phosphate industry, and the radium producing industries. However, from the viewpoint of a citizen, contrary to that of experts, the main distinction is likely between natural and artificial radionuclides (Sjöberg, 2000), or depending on the context in which radioactivity is used or originates from (Slovic, 1996; Perko, 2014). Therefore, such technical differentiation was not considered necessary in our study.

2.3 Methodology

To investigate how do stakeholders, including affected populations (residents), remediation experts, authorities, industry, and the mass media, perceive and experience uncertainties encountered during long-term environmental remediation processes at mixed chemical-radiological contaminated sites in Flanders, Belgium, this study employs a robust mixed methods approach. This includes media content analysis, semi-structured interviews with residents from affected areas, questionnaires, and a panel discussion involving remediation experts and authorities. While the mass media analysis effectively captured uncertainties during a specific period before, during, and after remediation, interviews and expert discussions documented uncertainties as remembered and recalled at the time of the interview or discussion. To strengthen reproducibility, we prepared a methodological guideline document and provided training for coders, interviewers, and analysts. The methodological guideline details protocols for data collection, analysis procedures and decision rules, and an ethical checklist (informed consent, anonymisation, GDPR compliance, and data management). The protocol specifies: (i) how questions were derived from prior literature and previously collected data; (ii) sampling strategy and subgroup definitions; (iii) procedures to ensure data collection consistency (standardised introduction, ordered question sequence, and prompts); (iv) interviewer, facilitators and coders trainings; and (v) data handling (recording, transcription, anonymisation, storage). It also includes participant feedback process (opportunities for participants to comment on and clarify preliminary findings). To capture temporal differences in the perception and experience of uncertainties, we recorded the timing of media article publications, structured interviews to elicit reflections on the past, present, and future, and asked the expert panel to discuss different stages of remediation rather than only the final outcome.

The study received independent ethical oversight from the project's ethics committee, which included ethicists from the Norwegian University of Life Sciences (Norway), University of South Bohemia in České Budějovice (Czech Republic), the University of Milan (Italy), and the Belgian Nuclear Research Center (Belgium). At the time of data collection, formal institutional ethics approval was not required under applicable policies. Nevertheless, we fully adhered to the principles of Ethics in Social Sciences and Humanities¹, ensuring that participants' as well as researchers' rights and well-being were safeguarded throughout the study.

To avoid bias, researchers had no prior relationship with interview respondents or expert panel participants, except for one co-author who had occasional collaborations with some experts but no dependency relationship. All authors are part of an independent social sciences and humanities group within a nuclear research centre, operating under the institution's ethical charter that safeguards scientific integrity. Additionally, student interviewers from different universities were engaged to ensure neutrality during interviews. There was no conflict of interest.

2.3.1 Media content analysis

Media content analysis followed the principles of Macnamara's methodological framework. (Macnamara, 2007). A sampling of media articles through electronic databases of national, regional, and local newspapers has been conducted using GoPress. GoPress was the central electronic press database in Flanders, offering digital access to a comprehensive collection of newspapers and magazines. It served as the primary platform for retrieving daily and weekly press articles, making it a widely used resource for media monitoring and research. At the time of the study, GoPress was the standard tool for accessing

¹ European Commission (2021). *Ethics in Social Science and Humanities*. Guidance prepared by Marjo Rauhala and Louiza Kalokairinou, DG Research & Innovation. Available at: <https://ec.europa.eu/docs/horizon/guidance> (accessed on 15th of August, 2025)

archived and current Flemish press coverage. The search string included keywords relating to the place of the case study (i.e. site); keywords combining in various forms terms referring to radioactive or natural radioactivity; pollution or contamination; and/or material, building or construction.

Table 2.1: Search strings per sites and key words (in Dutch) and number of hits

Site 1	
Word combination entered in GoPress	Number of hits
Olen vervuiling radioactieve	62
Olen vervuiling radioactief	54
Natuurlijk radioactief vervuiling	33
Olen bouw radioactief	21
Radioactief vervuiling bouw	18
Natuurlijk radioactief Olen	11
Natuurlijke radioactiviteit vervuiling	10
Natuurlijke radioactiviteit contaminatie	5
Natuurlijk voorkomende radioactieve materialen	5
Natuurlijke radioactiviteit Olen	3
Natuurlijk radioactief contaminatie	2
Site 2	
Word combination entered in GoPress	Number of hits
Natuurlijk radioactief vervuiling	36
Laak radioactiviteit	30
Tessenderlo vervuiling radioactieve	24
Radioactief vervuiling bouw	18
Tessenderlo vervuiling radioactief	12
Natuurlijke radioactiviteit vervuiling	10
Natuurlijk radioactief Tessenderlo	8
Natuurlijke radioactiviteit contaminatie	5
Natuurlijke radioactiviteit Tessenderlo	4
Natuurlijk radioactief contaminatie	2
Tessenderlo bouw radioactief	2

Articles found through the search were downloaded and screened for relevance and potential duplicates. The database consists of 369 articles published in Flemish newspapers in the period from March 1990 until August 2017 and specifically related to the two sites. From these, 164 articles were valid (123 articles were not valid, and 82 articles were duplicates).

A mixed qualitative – quantitative analysis involved multiple stages. Initially, each article was reviewed independently by two researchers from the team. They identified sentences that indicated uncertainties and collected metadata such as the article's date, publication details, information sources, quoted stakeholders, and references to specific sites. The research team extracted sentences in a database from media reports that highlight uncertainties, their causes, and their consequences in order to capture all relevant aspects. Any discrepancies in their extractions were resolved through discussion facilitated by the principal investigator. In the final stage, the extracted sentences underwent qualitative data analysis using thematic analysis. Two independent coders analysed the data, and a master coder oversaw the process to ensure consistency and reliability. Subsequently, a quantitative analysis was conducted based on the coding protocol developed from the thematic analysis results. During the analysis, the research team found it challenging to distinguish between uncertainty and its causes or consequences. As a result, the findings presented in the result section reflect all aspects.

2.3.2 Semi-structured interviews with community members

Semi-structured interviews with community members followed the methodological framework of (Fylan, 2005), (Harrell et al., 2009). Interviews were conducted in 2018 with members of the local population living in or around the two areas with historical radioactive contamination due to metal processing and radium industry (N=17) and the phosphate industry (N=7), respectively. The number of interview participants was not predetermined; instead, individuals were purposively recruited until data saturation was reached—that is, the point at which no new themes or insights emerged from additional interviews. In research, saturation is typically achieved between 12 and 20 interviews (Hennink et al., 2022), which was consistent with this study. The sampling method consisted of door-to-door interviews of residents living in specific streets in the associated villages. The selection of the streets was based on contamination data and remediation strategies. Interviewers visited all households located on the designated streets over several days and at different times of day to maximize participation. These locations were rural areas, typically consisting of small rows of houses. Although we did not systematically record the number of residents approached and are therefore unable to report a formal response rate, our procedure ensured that all households in the targeted locations were given the opportunity to participate. Respondents received a leaflet with information and objectives about the study, as well as the person to contact for any future questions.

The pre-defined list of topics for the semi-structured interviews was derived from document analysis and media analysis (Guillevic et al., 2018; Perko et al., 2019). This list entailed four themes: socio-demographics, behaviour, risk perception and NORM. *Demographics* included zip-code, gender, year of birth, occupation, level of education, number of family members (incl. children below 16 years), years living in area, choice for living in area. The topic *behaviour* referred to behaviours in and around the house, including renovations to the house such as installation of a ventilation system, home growing of vegetables and organisation of outdoor activities. *Risk perception* related to environmental pollution and associated thoughts, feelings and perceptions. A specific topic *NORM* and radioactivity were added at the end of the interview to assess the level of knowledge on the term, and the knowledge on and understanding of both the contamination and remediation strategies.

A mix of descriptive, structural and contrast questions was used, in order to provide the widest range of information. Descriptive questions allow the interviewee to answer in a narrative that may include insights that researchers had not considered themselves yet (Harrell et al., 2009). Structural questions aid researchers to understand relationships, while contrast questions aid researchers to understand terminology (Harrell et al., 2009). As research into societal uncertainties related to living on /next to a site contaminated from historical pollution due to radium or phosphate industry is novel, we have used mainly descriptive questions to allow for the identification of new insights and new uncertainties. This included general questions (opening questions), followed by more specific questions based on the interview protocol. We note that in research areas that are novel with respect to the topic of research or the research area in which it is conducted, a specific type of descriptive questions, namely native language questions (e.g. “How would refer to ...”) should be asked to determine specific terms used by the sample population.

Interviews were recorded and transcribed. Informed consent was asked orally from the respondents, guaranteeing their anonymity.

Interview transcripts were then analysed using a combination of inductive and deductive coding analysis. Coding is a method of qualitative data analysis (Lofland et al., 2005) that allows for the management and organisation of data according to emerging frequent, dominant or significant themes (Abelshausen et al., 2015; Thomas, 2006). It also enables the identification of relationships between theories and case-by-case comparisons (Gibbs, 2007). As coding is an interpretative act that depends on the coders’

academic discipline, their ontological and epistemological orientations, and the theoretical and conceptual framework (Saldaña, 2009), consistency needs to be strived for. For this study the internal consistency of the coding analysis was strived for by basing the coding system on the description of uncertainties derived from media analysis (i.e. topic list). The initial coding corresponded to the aforementioned three main topics (excl. demographics). Within each of these codes, deductive analysis was applied to allow for the emergence of new themes and insights.

2.3.3 Expert panel

An expert panel was organised in March, 2019. An invitation letter was sent via email to the identified key stakeholders for the investigated sites. This invitation letter was accompanied by a brief introduction to the case study and a survey. Invited participants were asked to complete this survey regardless of their availability to participate to the subsequent panel discussion. Among others, they were asked to describe the scientific and societal uncertainties they may have been confronted with in the decision process concerning the environmental remediation process or the end use of the site. They were also asked for suggestions to better account for these uncertainties in decision-making, as well as general recommendations for improving decision processes. Five experts returned the filled in questionnaire.

The stakeholders (N=10) that participated to the panel were experts in their respective field: federal and Flemish government representatives, industry representative, soil remediation consultancy firms, and members of a nuclear research centre. As an introduction to the discussion during the panel, two presentations were provided: one on standard procedures for decision-making in soil remediation and the other on the sites. Additionally, the results of the expert survey, along with the results of the interviews with local population and media analysis were presented during the panel discussion. The discussion held during the panel with technical experts was centred around three questions: Is it possible to reduce societal uncertainties? In what manner can societal uncertainties be reduced? Can stakeholder participation be an added value in the reduction of uncertainties?

2.4 Results

2.4.1 Uncertainties identified through mass media analysis.

Initially, our goal was to understand how uncertainties are perceived and experienced; however, during the analysis, we noticed that the media often reported on both the causes and consequences of these uncertainties instead. Differentiating between these categories proved challenging. As a result, 13 categories of uncertainties, along with their causes and consequences, were identified in the 164 newspaper articles (Table 2.2). Our findings reveal that each site has unique characteristics regarding uncertainties reported in the mass media. For Site 1, the most reported uncertainties pertain to remediation management, financial matters, and legal issues. In contrast, Site 2 primarily faces uncertainties related to public and environmental health, remediation management, and ambiguity about the problem. Below, we provide a brief explanation of each category to clarify their meanings and context. It is important to note that media attention to uncertainties shifted over time. For example, once the uncertainty regarding who would bear the costs was resolved, this issue no longer appeared in the mass media.

Table 2.2: Uncertainties identified through mass media reporting.

Topic	Number of references for Site 1	Number of references for Site 2
Remediation management	52	26
Public and environmental health	35	39
Financial and legal matters	42	17
Ambiguity about the problem	30	25
Waste management	21	4
Contradiction in opinions	9	14
Communication problems	13	2
Contradiction in opinions	8	6
Lack of trust	9	4
Timing and duration of remediation	7	4
Responsibility for the pollution	4	6
Future concerns	5	1
Reputation on the polluter	2	0

Uncertainties regarding remediation management during the planning phase, as reported in the mass media, revolved around several key issues. These included questions about the methods and scope of remediation, such as how it would be conducted and the extent of land requiring treatment. At one site, local input was sought through a working group, but concerns arose among locals about transparency and doubts about the effectiveness of the remediation efforts. Other uncertainties stemmed from ambiguity surrounding whether private properties would be remediated by industry or by residents themselves, and concerns about the treatment of emotionally significant areas like cemeteries. Locals also expressed fears about protecting their homes during waste transport to prevent any adverse effects. Questions were raised about the inconvenience caused by the remediation process itself. The timing of decisions and the subsequent implementation of those decisions emerged as a significant source of uncertainty. The remediation process, being complex both administratively and technically, saw media reports highlighting delays in political decision-making, negotiations between stakeholders (often financial in nature), and procedural hurdles such as licensing delays. Additional uncertainties arose regarding the origin and severity of contamination (e.g., whether it was solely historical), and concerns about the potential subdivision of the site into smaller project units.

Uncertainties related to public and environmental health stemming from contamination raise significant issues regarding potential declines in overall quality. Ambiguity about the issue arises from insufficient or unreliable information regarding contamination and guidelines for protecting oneself. There are also uncertainties about the impact of the remediation project on societal and cultural life. In terms of environmental health, uncertainties surround whether the remediation efforts will negatively impact the visual aesthetics of the surroundings, including the preservation of green areas within neighbourhoods. At one site, locals recalled instances where individuals in protective gear (white overall, mask with a filter, gloves) conducted radioactivity measurements in a village. The measurement results at one point revealed larger areas of radioactive contamination than initially anticipated, including private gardens that may need to be abandoned. Questions persist regarding whether these areas can still be used for residential purposes, as reported in mass media. Concerns were also expressed about the potential introduction of "dangerous substances" into the food chain, such as through cows grazing on polluted grass. Moreover, there was also uncertainty about whether land use should change due to contamination and the potential effects on groundwater and wildlife in rivers, as well as plans to mitigate these impacts. The impact of radioactivity from local industries on public health is another area of

concern, with questions raised about the safety and quality of life in areas adjacent to industrial sites. Concerns about specific risks to children contribute to existing uncertainties. For example, while residents outside the contaminated area are assured of no health risks, media reports indicate lingering concerns about the potential for cancer development. In contrast, residents in contaminated parts of the villages may express less concern, often citing job security and the absence of severe environmental impacts, such as the absence of animal deaths due to pollution, as reasons for their perceptions.

Financial and legal uncertainties revolve around the costs associated with pollution and its remediation. A major concern is determining who will bear the costs for cleaning up contaminated grounds and waterways. Long-term financing uncertainties stem from disagreements and lack of clarity on funding sources and the methods of financing (e.g., incremental or lump-sum payments). Residents and workers in affected areas fear potential job losses in local industries. Locals also worry about the possible depreciation of property values due to pollution. Farmers, promised compensation for the impact on their agricultural activities, remain uncertain about when they will receive it. Concerns about transparency are prevalent, with some feeling that information is not being fully disclosed due to financial consequences. Delays in finding solutions fuel scepticism and raise questions about daily risks in contaminated areas, such as consuming home-grown vegetables or allowing children to play outside.

Ambiguity about the problem: Conflicting laws and norms further contribute to ambiguity. Legacy sites highlight the challenge of industries acknowledging current issues resulting from past practices that were legal at the time. There is also a call-in media articles for new environmental surveillance by authorities to address inconsistencies in knowledge about the contamination and provide crucial information.

Reported in the mass media, **uncertainties regarding waste management** after the remediation also provoke concern, especially given the long half-life of certain radionuclides. People question whether the structures intended for storing waste after remediation will be adequate for such extended periods. Additionally, there are uncertainties about the specific quantities, redistribution, and destination of radioactive and metal waste. Furthermore, concerns are voiced over the perceived delays in implementing effective waste management strategies. Questions linger about where the waste will be stored, and the methods involved—whether it will be temporary or permanent.

Uncertainties arising from contradictions in opinions were quite common in the media analysis. At times, parties, particularly industries, asserted that no radioactive or chemical materials had ever been detected, sparking debates with local authorities. This contradicted the historical evidence of contamination. Disagreements also surfaced between industries and political entities, as well as between locals and industries. For instance, while communities accused industries of reluctance to address pollution issues, industries countered by claiming commitment to remediation and prevention of further emissions. Additionally, conflicting opinions emerged regarding financial responsibility for remediation, with ministers advocating for polluters to bear the costs while industries argued compliance with existing laws absolved them of responsibility. Similarly, contradictions in mass media messages contributed to uncertainties, for instance:

- Initially, assurance of safety was followed by sudden notification of contamination after decades of perceived normalcy.
- Assertions of safe proximity to rivers were contradicted by measured radioactivity.
- Debate arose over whether industries or private owners should be responsible for remediation.
- Despite assurances of safety, remediation efforts or restrictions on inhabiting certain areas were deemed necessary.
- Soil usability conflicted with contaminated groundwater.
- While new construction was deemed safe, environmental impacts on fish and vegetation suggested otherwise.

Uncertainties stemming from communication issues highlight perceived shortcomings or ineffectiveness in communication between scientists, politicians, and the local population, as well as between responsible ministers and mayors of affected communities. For example, unclear communication occurred when people discovered the issuance of a soil certificate without direct communication from the industry itself. Delays and ambiguity in communicating measurement results and responsibility for addressing issues further exacerbated uncertainties. In some instances, it is argued in mass media that ineffective communication, rather than actual risks, is the primary cause of problems.

Uncertainties stemming from a lack of trust constitute another significant theme in societal uncertainties reported in mass media. This is evident in perceptions, as reported in the media, that the government does not take the issue seriously, often downplaying its significance or showing reluctance to take action. Additionally, there is a perception that the government bears a responsible role in the entire problem. There is also a lack of trust in the industry. Some people believe that the industry has provided false information to politicians regarding the waste content, leading to a lack of transparency. Furthermore, a visit by a political party to the contaminated site was perceived as an unhelpful media stunt, further eroding trust in the handling of the situation and increasing uncertainty about whom to trust.

The timing and duration of the remediation frequently emerged as a significant uncertainty, as reported in mass media, particularly regarding its start date. The high cost of remediation often prevents areas from being remediated simultaneously, leading to considerable delays. Furthermore, the storage of waste tends to take a long time to implement, and delays were also reported in the investigations required for remediation.

Uncertainty regarding responsibility for the contamination and remediation was a persistent issue. For a long time, it remained unclear who was accountable for the pollution, leading to extensive debate. Authorities sometimes asserted that the polluter was responsible, while at other times, they claimed that the industry did not bear full responsibility, citing reasons such as the inability to meet legal norms. The industry, on the other hand, consistently maintained that the fault was not entirely theirs.

Future concerns, as reported in mass media, include concerns about the prosperity of their village. Residents are uncertain if the industry, which provides many local jobs, will continue to operate. Farmers worry about whether their lands will remain viable for agriculture in future. Additionally, there are fears that polluted areas will remain contaminated for a long time, potentially diminishing the overall quality of life.

As reported in mass media, there is **uncertainty regarding the reputation of the polluter**. The industry fears a decline in its reputation and has emphasised its commitment to remediating the contaminated ground.

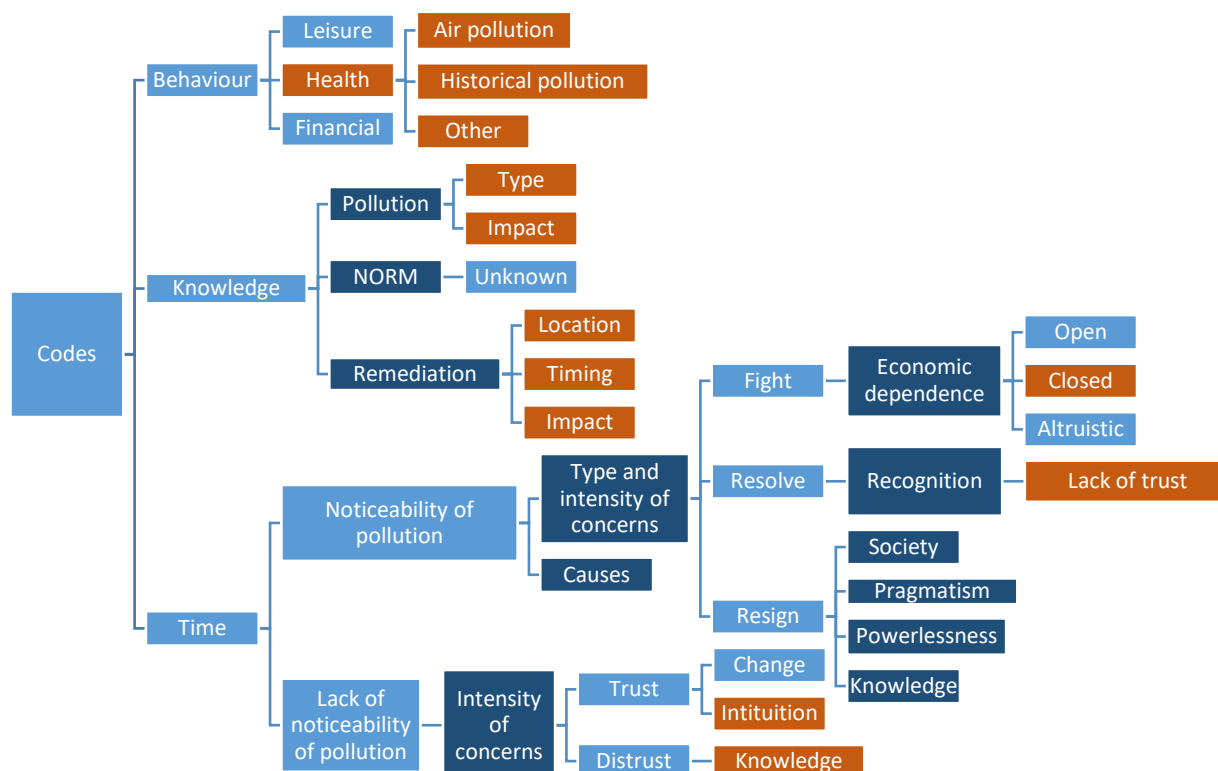
2.4.2 Uncertainties identified through interviews with local community members.

The analysis of semi-structured interviews with local community members revealed three dominant themes or codes: [behaviour], [knowledge], and [time] (Figure 2.1). We explain these themes and their context in this section. However, during the discussions, interviewees often referred to the causes of societal uncertainties rather than focusing solely on the uncertainties themselves. Therefore, similar to the media analysis, we present both aspects.

The first notable finding concerns the divergence of the main codes from the initial topic list, stemming from a divergence in perception and experiences as expressed by the interviewees. For instance, no [risk perception] theme emerged from the interviews regarding concerns over NORM contamination or

historical pollution in general (whether mixed, chemical, NORM-related, or otherwise perceived). Instead, interviewees sometimes expressed risk perceptions unrelated to the interview topic, as illustrated in the following quote: "[Home-grown vegetables] are tastier, but healthier I am not sure [...] because of air pollution, planes that fly over." The predominant theme that emerged concerning perceptions of risk was [time]. The influence of time on risk perception within the context of historical pollution proved significant and thus emerged as a novel code in the analysis.

The same is the valid for initial code [NORM] (topic list code), which did not emerge as a main theme in interviewees' responses. Instead, the main theme that arose in the analysis is linked more strongly with [knowledge] (or lack thereof) of the concept NORM, the associated pollution and remediation.



Legend: causes of societal uncertainties are 'dark blue'; societal uncertainties are 'dark orange'

Figure 2.1 Key Codes Identified from Interview Analysis

Behaviour

The code [behaviour] included uncertainties, or lack thereof, directly related to people's everyday behaviour in and around their houses. Given the context of historical pollution, the choice was made to inquire about people's everyday behaviour in their private garden and their leisure time. As explained in section 2, the phrasing of the questions and the content of the discussions was designed such that an unbiased insight in societal uncertainties expressed by people living in areas with historical contamination could emerge. The analysis reveals that interviewees did not tend to perceive their direct environment (i.e. house and garden) as contaminated, when no reference is made to this contamination. This is illustrated in the following quote on leisure time in the garden *"I really love being outside [in my*

garden] [...] [I organise] sometimes a barbeque with friends". Additionally, when querying about vegetable gardens, little to no spontaneous mention is made of contamination "[I have a vegetable garden and] I am happy about it". The analysis reveals two main reasons for having a vegetable garden, besides [leisure], namely [financial] and [health] considerations. In themselves, these reasons are not perceived as an uncertainty; people perceive homegrown vegetables as cheaper than those available for purchase and, *in general*, as healthier. The main reason why these are perceived as healthier is the ability to control what, if any, pesticides are used on home-grown vegetables "[...] does not use pesticides and [...] are biologically, not 100%, but biologically grown."

The code [health] is however considered as a societal uncertainty as some interviewees indicate they are unsure about whether home-grown vegetables are healthier than those available for purchase "[Home-grown vegetables] are tastier, but healthier I am not sure". This stems from pollution being either [air pollution], [historical pollution], or [other]. "Air pollution, planes that fly over, I am not sure. Yes, and cars. Before when we worked, then a car was still new but now with all these new houses, now you never know". One interviewee refers to the industry in the surrounding area, although no specific mention is made of the type of industry or the company responsible. The interviewee however links this industry to air pollution that might contaminate home grown vegetables. "Tastier definitely, healthier yes... that depends on what fall into it. Here they are not sprayed. But yes, I am not sure, I do wonder... there is some industry in the area...". This type of societal uncertainty results not directly in an actual concern rather than in a sense of resignation "Concern is a big word; there is not much you can change as an individual. My father he used to be active in an environmental organisation and then you know, as an individual there is little you can do against a big commercial industry".

Knowledge

The code knowledge emerged because of a "lack of knowledge" on the concept of NORM, the contamination, and the remediation. The code [Pollution] is used to refer to contamination. Interviewees did not express a specific form of contamination and described the impact of the industrial process (historical) as pollution. However, it needs to be noted here that, as the interviews were taken in Dutch, the Dutch language, especially in laymen terms or in local dialects, does not easily distinguish between pollution and contamination. The term pollution is therefore used as code; no conclusions can however be drawn as to whether a lack of knowledge on the type of 'pollution' influences the distinction between contamination and pollution.

The analysis reveals that interviewees have little to no knowledge of what the term [NORM] means; two interviewees indicate they have heard of it, but do not know what it is. "[I know it exists] Yes, like I know CO exists". One interviewee links it to materials such as asbestos: "of asbestos, from those sheets. Yes, we have those here...".

Concerning [Pollution], the analysis reveals that interviewees have all at some point experienced pollution resulting from the industrial process [Impact]; however, they have very little to no knowledge on what [type] of pollution is/was present in their area.

The code [Remediation] encompasses interviewees' knowledge on the remediation strategy applied for the historical pollution. Three subcodes emerge from the interviews, namely [Location], [Timing], and [Impact]. The code [Location] represents a significant uncertainty concerning the exact areas of remediation. When interviewees are aware of remediation activities, they can provide an approximation of the areas that have been remediated. However, none of the interviewees can provide a detailed and precise location of remediation. "Yes, remediation, and is that river not in [name of village]? Yes, but it can also be in another village, I am not sure. I follow it on the website." Furthermore, uncertainty exists concerning the timing of the remediation. Some interviewees from both sites indicate that the remediation happened in the past, while others indicate they think it is happening now. "Yes, how long

have they been doing this, 2 months, a month and a half. I am not sure when they started.” “Yes, I remember this from school”.

Concerning the codes [Location] and [Timing] it needs to be noted that although little knowledge exists on remediation strategies, little to no reference is made to whether this lack of knowledge on the remediation strategy also leads to a societal uncertainty. Several interviewees indicate that they do not need to know all the details as the responsible parties ‘know what they are doing’ (*“The company and the government they know what they are doing, they will remediate those places that are necessary”*) or the contamination is not considered as dangerous (*“Whether it is really dangerous, I don’t think so. There are sheep walking around there so it will not be that bad”*). These expressions, indicating a lack of uncertainty are included in the code [Impact]. This third code [Impact] therefore refers to the interviewees’ perceptions on the necessity of the remediation, which is experienced either as a certainty or an uncertainty. Trust in the responsible remediation actors is not absolute. The code [Impact] therefore also includes uncertainties related to the ‘hope’ that in case remediation is necessary, it will be done. *“Oh, people are living close to there, so if it was really necessary for safety, then I suppose that it would have been remediated, I hope.”*

Time

The third code that emerges from the analysis is [Time]. In contrast with the code [Timing] (see Knowledge), [Time] is not a societal uncertainty in itself; however, the timeframe in which the historical contamination is discussed does influence the type of societal uncertainties that exist. As can be noted in Figure 2.1, a distinction is made concerning pollution as it is now and as it was 30 years earlier, resulting in different societal uncertainties, with a different degree of intensity. The main distinction between now (i.e., 2018) and 30 years earlier is that 30 years ago the pollution was noticeable. Interviewees provide clear descriptions of their personal experiences with the pollution at that time. The most often referenced pollution is air pollution, noticeable through smell. *“[...] Until, let’s say, 30 years ago there was often odour pollution. This was when the air was wrong, I think, I think that with this air also particles came that normally should not be there. [...]”*. When interviewees describe the situation at the moment of the interview it is noteworthy that as the smell has disappeared or has significantly been reduced, the perception exists that the pollution has also disappeared: *“[...] Now it is still, once in a while, rarely we still have odour pollution [...] I do not think there is still a lot of pollution, I personally do not think so.”*

Noticeability of pollution

When pollution is noticeable [Noticeability of pollution], the intensity of concern is greater. Additionally, interviewees additionally provide a description of the cause of the (noticeable) pollution ([Causes]). For instance, interviewees describe the source of the odour pollution and the actor responsible for it. *“[...] here at the river, wastewater from the plant was discharged in the river. And that had a serious smell.”* Besides odour pollution, different types of pollution were noticed 30 years earlier and described by the interviewees in details. For example, one interviewee talks about an episode in that time: *“When we planted several trees, we left on holiday for 14 days. When we came back all the leaves were on the ground. Like it was fall, but it was summer. So, I said this is not possible. [...] people said there had been green rain. What it was, I do not know, because I did not see it. And then the plant bought us new trees. [...] Every time something was destroyed (e.g. [stockings were sifted with little holes]), the plant paid for it.”*

The analysis reveals that three types of responses to the noticeable pollution: [Fight], [Resolve] and [Resign]. The first response [fight] entails three types of societal uncertainties (or the lack thereof), directly linked to economic dependency: [Open], [Closed], [Altruistic]. Economic dependency describes two types of people: economically dependent and economically independent. Economically dependent

people are those who work (worked) themselves at the plant or have close relatives/friends who work (worked) at the plant. Economically independent people are people who do not work at the plant, or who have no close relatives/friends who worked at the plant. The response to the pollution by economically independent people was [open] or at least perceived as open. *“Yes, the active people (cfr [those that addressed the pollution]), that were people that did not work in the factory, who made their living somewhere else.”* Economically dependent people had a [closed] response as illustrated by the following quote: *“The sympathizers were too afraid to be open about it, they did not like it, the smell and everything, that is not nice for people. But they always had someone in the family who worked there, so it was a bit dubious.”* There is however an exception to this dichotomy, namely the altruistic response. Some of the economically dependent people did address the issue openly. *“At that time, there was also a Don Quixote or something that worked there but tried to change something.”* As the interviewees do not give any indication of uncertainty when describing the open and altruistic response, these responses are not perceived as societal uncertainties. However, as the closed responses are described as a ‘dubious’ situation, a certain degree of societal uncertainty is expected. However, it needs to be noted that a closed response based on a certainty of negative repercussions due to an open response for economically dependent people (e.g., getting fired) is not considered as a societal uncertainty.

The second response [Resolve] entails the active addressing of the consequences of the pollution. About 30 years, respondents say people experienced higher degrees of lung issues than normal for the region, perceived to result from the pollution. These lung issues were actively addressed by seeking medical attention. The societal uncertainty related to this is not the (perceived) consequence of the pollution, but the resulting lack of trust in the government and the plant. This lack of trust is expressed by the interviewees as a societal uncertainty as it is indicated that people were uncertain about which actors could be trusted or whether any of the involved actors could be trusted at all. The following quote provides an illustration of what the codes [Resolve], [Recognition] and [Lack of trust] entail: *“I will tell you the following. We have a daughter; she is now 37. When she was 3 or 4 years old, she had a bad cough. At night she was always coughing. I do not know if you know the symptom of false croup, as people say. That is very bad cough and that is what my daughter had. Here at the general practitioners, antibiotics, and more antibiotics and then we went to the University Hospital. And that doctor or professor, with the file still closed in his hands, after he asked about the symptoms, and we said this. The doctor then said: “ha, you must be from (name of village). That was in 83-84. Yes, it’s something that has always stayed with me. Yes, that is a serious thing when the doctor says that. [...] And the plant, they do not provide any info. They could, but yes... they will probably make advertisement for themselves so... who can judge whether it is objective...”*

The third response is one of resignation ([Resign]). Resignation is expressed by interviewees in four different manners: [Society], [Pragmatism], [Powerlessness] and [Knowledge]. Societal resignation ([Society]) is illustrated by the following quote: *“No, that was a period, when you are young you do not worry that much. Now, young people they are more environmentally conscious, but in this day, we did not think about it.”* A third expression, i.e. [Pragmatism] entails a general sense of resignation: *“If you have to be worried about this, then you would not sleep anymore at night, so I don’t.”* Furthermore, resignation is also expressed as a result of [powerlessness]: *“When you have a father who used to be active in an environmental organisation, then you know that as an individual there is nothing to do against a big commercial industry.”* A final expression of resignation [Knowledge] is illustrated by a lack of knowledge of the actual situation. *“Yes, so the control has improved, but what is released into the air, that, I think, we will never know. [...] so, I do not need more information.”*

Lack of noticeability of pollution

When there is a lack of noticeability of pollution, the intensity of the concerns is less than when pollution is noticeably present. This lack of noticeability is related to the current situation and entails among

others, the absence or reduction of odour pollution. *“Now it is, once in a while, rarely, that we have odour pollution”*. This absence of odour pollution and a lack of noticeability of pollution in general is directly linked to [Trust] in responsible actors and current measures [Change]. *“[Presence of pollution in area] Not, that I know of, I think that nowadays, the chemical industry has to decently clean up, so I do not think so.”* Furthermore, a sense of trust in ones’ own judgement can be noted [Intuition]. This trust is however not absolute and can lead to uncertainty. *“[Intuition] No, actually not, no. We have been living in (name of village), practically 30 years and never anything. That however probably does not say very much”*. Moreover, there is also distrust in responsible actors and current measures resulting from perceived misinformation or a lack of transparency [Knowledge]. *“What does worry me, and which is becoming perhaps a trend is that when there is a fire in a plant, you have to keep doors and windows shut, but the cloud that comes over is not toxic or anything. That is said like this and then you wonder whether the plant is telling the trust.”*

2.4.3 Uncertainties identified through discussions with experts and uncertainty management

Uncertainties identified through a survey and panel discussion with experts, including authorities, encompass both technical and societal dimensions. **Technical uncertainties** highlighted include the logistics of consolidating waste from multiple disposal sites into a single repository and uncertainties arising from varying ground characteristics. **Societal uncertainties**, as perceived by experts, include challenges such as managing conflicting needs and desires, determining future land use post-remediation, addressing unmet expectations, reconciling public expectations with scientific imperatives for remediation, uncertainties related to financial responsibilities, and effectively communicating the trade-offs between cost-benefit considerations and complete contamination removal.

To address uncertainty management, the expert panel initiated a discussion on involving the population in decision-making processes. Several participants noted that they do not engage directly with the local population daily. Instead, they relay information to the local municipality, which is viewed as responsible for communicating with residents. The panel acknowledged the crucial role of local municipalities, including mayors and environmental officials, in fostering community engagement. They emphasised providing municipalities with necessary information to facilitate effective communication.

Another specific element to the case-study site, is the employment of many people in the vicinity by the involved industry. Participants argue that this resulted in people having more knowledge of the situation and therefore more expertise and trust. Panel participants argue that by giving employees the right information on environmental aspects, they can share this in leisure time in a correct manner with their family and friends.

It is noted by the panel that the public needs to have trust in what an expert does, and this trust is something you need to earn by being trustworthy and by passing on important values such as transparency. In the case-study site, the historical pollution was a result of the previous legal framework allowing these discharges; this situation did however need to be remediated. As the responsible industry is remediating the site, this was considered a positive evolution and deemed to ensure trust with the local population. Building trust is seen as a key factor, notably trust in what is communicated. An example given is the organisation by the industry of open days to give the opportunity to employees to invite their friends and family to visit the plant. Another example is the “info-market” organised by the neighbourhood in relation to the remediation project. During this market, information was not provided in group-format, but everyone could ask personal advice making the information discussed understandable and actionable. A note is however made, that communication needs to be adapted to the remediation that is ongoing. The example is given that communication in the starting phase, when not everything is known is different from communication in a later phase when a lot more information is

available. Open and regular communication is therefore considered as important and is deemed to contribute to changing a rather negative atmosphere into a more positive one.

Actual participation of the local population to the decision-making process is considered as possible by the experts but is rather limited. Participants argue that the decisions on how activities need be carried out should be left up to experts. Moreover, public engagement is seen as involving mainly the government, as the vision of the public is deemed to be often limited and driven by personal interests. At the same time participants agree that remediation projects can be modified based on reactions from the public. Participation is for instance seen as necessary when the project experiences difficulties. This does however entail that residents might have expectations that cannot be fulfilled; complete remediation may for instance be expected, but not feasible. Furthermore, panel participants recognise the importance that community members who join in public meetings are open to be informed. They argue that although community members participating in meetings are not always positive, but their willingness to join allows room for discussion, such that questions can be answered, and solutions can be found. For this reason, participation in public meetings is highly appreciated by the panel stakeholders. They argue that difficulties mainly arise when people are not willing to join in. Close cooperation with municipalities is seen as important to attract people to public meetings.

2.5 Discussion

This study is the first to systematically and holistically investigate how uncertainties are perceived and experienced by local populations, industry, authorities, and remediation experts, while also examining how these uncertainties are reported in the mass media throughout the different phases of environmental remediation processes. For this, two case studies were conducted, focusing on historical mixed radioactive-chemical contamination in Belgium: one from the legacy radium industry and another from a NORM site associated with the phosphate industry.

The primary finding concerns the complexities surrounding uncertainties, encompassing their origins and impacts. While the study preliminary defined uncertainties based on scientific literature (Guillevic et al. 2018), distinguishing between uncertainties, causes, and consequences proved challenging. Therefore, a comprehensive approach to understanding perceptions of and experiences with uncertainties was adopted, as applied in a case investigating uncertainties in radiological events by Hoti et. al (Ferdiana Hoti et al., 2021). This approach allowed for insights into how uncertainties (causes and consequences) are perceived and experienced, how do they manifest, evolve, and interact across various stakeholder groups, societal contexts and time.

The second finding pertains to the framing of the problem. Each stakeholder group frames uncertainties, causes, and consequences differently. For instance, even the origin of the problem is framed differently: mass media typically refers to it as "radiological contamination," experts describe it as "mixed contamination" (encompassing both chemical and radiological aspects), while residents in the affected areas perceive it more broadly and simply as "pollution." According to Henwood et. al, understanding risk framing is crucial for comprehending participants' perspectives, orientations, and contextual understandings (Henwood et al., 2008).

The third finding highlights the diverse nature of uncertainties across stakeholder groups and contaminated sites found in a previous study investigating the definitions and types of uncertainties related to radiation risks (F. Hoti et al., 2020). Mass media reports underscore uncertainties in remediation management, including questions about remediation methods and the extent of land requiring treatment. There are also uncertainties surrounding financial and legal matters, particularly concerning legislative responsibilities for remediation costs. Additionally, concerns about public and environmental health persist, especially regarding the safe residential use of contaminated areas.

Contrary to media reports that emphasise conflicts, low trust, and ambiguity, interviews with residents living in high-risk areas revealed that their behaviour was not notably influenced by potential contamination. Many did not perceive their immediate surroundings, such as their homes and gardens, as contaminated unless specifically informed of such contamination. In contrast to media narratives, most respondents expressed high societal trust in authorities and operators to effectively remediate polluted environments as necessary. Moreover, the knowledge theme uncovered that despite relatively low awareness of radiological or NORM contamination among residents, this did not translate into widespread uncertainties among them.

The most significant discrepancy in uncertainties and concerns was identified between experts (remediation experts, authorities, and industry) and residents. This is unsurprising, as differences in the perception of radiological risks between experts and laypeople have been investigated and confirmed as well in (Perko, 2014) and (Sjoberg, 1998). Experts primarily focused on technical uncertainties, such as the logistics of consolidating waste from multiple disposal sites into a single repository and uncertainties arising from varying ground characteristics, as confirmed by other technical studies (Popic et al., 2023). Notably, experts expressed rather low trust in the affected population. They highlighted societal uncertainties related to managing conflicting needs and desires, determining future land use post-remediation, addressing unmet expectations, reconciling public expectations with scientific imperatives for remediation, and achieving trade-offs between cost-benefit considerations and complete contamination removal. It is worth noting that stakeholders at each site exhibited different uncertainties, influenced by the site's history, as well as its socio-political and economic context as already indicated by (Perko et al., 2017).

When discussing societal uncertainties, it is crucial to recognise that these uncertainties are interrelated and do not exist in isolation (Renn, 2008). This study demonstrates that the type and intensity of uncertainties experienced are influenced by their interrelationships. Therefore, societal uncertainties should not be addressed as a mere 'ticking of boxes' exercise but should be approached by acknowledging and understanding these complexities.

A key factor affecting the type and intensity of uncertainties related to environmental remediation is temporal discrepancy. Over time, not only do uncertainties change, but their intensity also fluctuates. In some cases, the intensity decreases to the point where specific uncertainties may disappear altogether. Various reasons contribute to this temporal discrepancy. Societal uncertainties experienced by residents are influenced by the zeitgeist, or the prevailing societal and political climate. For example, air pollution was a prominent issue on the political and societal agenda, receiving significant media attention. As a result, societal uncertainties were experienced differently, with their intensity directly related to the zeitgeist. Additionally, some uncertainties, such as financial concerns about 'who will pay,' were resolved as decisions were made between the time of acute pollution and the interviews. The visibility or invisibility of pollution, or the 'noticeability of pollution,' also affects the intensity of uncertainty, which can change over time and explain temporal discrepancies in legacy sites.

Given these findings, we recommend that when addressing societal uncertainties, remediation actors should assess not only the site-specific characteristics but also the broader context in which affected populations live, considering their everyday lives and the evolving nature of uncertainties over time.

This study has several limitations that should be acknowledged. First, the number of interviewed stakeholders was relatively small, although we achieved data saturation, which may limit the representativeness of their perspectives. The findings should therefore be interpreted as providing in-depth insights rather than generalisable conclusions. Second, cultural and linguistic specificities may have influenced the interpretation of remediation-related concepts, particularly in translation. Third, naturally occurring radioactive material (NORM) was relatively unknown to many residents, which may have shaped their perceptions and the way they expressed uncertainties. Finally, the presence of new

residents in some of the affected areas may have influenced the continuity of local knowledge and experiences regarding contamination and remediation.

2.6 Conclusions

Our study showed that uncertainties related to historical pollution from radium or phosphate industries manifest, evolve, and interact across various stakeholder groups, societal contexts, and timeframes. As each stakeholder group (including citizens) faces different uncertainties and frames them in specific ways, stakeholder engagement is essential in all steps of remediation processes, to make these differences explicit, and increase the mutual understanding of concerns and related behaviours. While experts (authorities, industry, scientist), focus mainly on technical aspects, and are faced with social uncertainties about conflicting needs, future land use, and reconciling public expectations with scientific imperatives, some residents revealed other sources of uncertainties, for instance the location and time where has taken place or - at the time when pollution was visible - not knowing which actor is trustworthy. Results also showed that although similar, each site's uncertainties were influenced by its history, socio-political, and economic context, substantiating the need for social studies and context-sensitive solutions to site remediation. The study further demonstrated the interrelationships between the various societal uncertainties and the temporal discrepancy, as societal concerns change with time and some uncertainties get resolved.

Addressing societal uncertainties thus requires acknowledging their complexities and considering the broader context of affected populations' everyday lives and the evolving nature of these uncertainties. This approach is crucial for ensuring the sustainability of remediation efforts, as it fosters more inclusive, adaptive, and resilient strategies that are attuned to the dynamic needs and concerns of all stakeholders involved.

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3. Final Conclusions

WP6 explored strategies to bridge the value–action gap across diverse stakeholder groups, using two case studies on radon and NORM. The radon study demonstrated that while effective mitigation measures exist, low uptake persists due to barriers such as limited awareness, fragmented processes, and insufficient communication. Addressing these challenges requires integrated, multi-stakeholder interventions that extend beyond residents to include policymakers, contractors, and health professionals.

The NORM study revealed the multifaceted nature of uncertainties in long-term remediation projects, shaped by historical, socio-political, and economic contexts. Stakeholders differed in how they perceived and prioritised uncertainties, highlighting the importance of inclusive dialogue and trust-building in decision-making processes.

Together, these studies emphasise that effective radiation risk management depends not only on technical solutions but also on addressing social, institutional, and communicative dimensions to foster informed engagement and sustainable action to protect from radon or/and NORM exposure situations.