Department of Mathematics and Systems Analysis

Novel methods of scenario analysis for the probabilistic risk assessment of nuclear waste storage and disposal facilities

---

Edoardo Tosoni

Aalto University

POLITECNICO
DI MILANO

DOCTORAL
DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 104/2021

Novel methods of scenario analysis for the probabilistic risk assessment of nuclear waste storage and disposal facilities

Edoardo Tosoni

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of Aalto University (Finland) and Politecnico di Milano (Italy), at a public examination held at the lecture hall H304 of the school on September 14, 2021 at 12:00.
The public defense will also be organized via remote technology.
Link https://aalto.zoom.us/j/64272127247; Zoom quick guide: https://www.aalto.fi/en/services/zoom-quick-guide
This doctoral thesis has been conducted under a convention for the joint supervision of thesis at Aalto University (Finland) and Politecnico di Milano (Italy)

Aalto University
School of Science
Department of Mathematics and Systems Analysis

POLITECNICO DI MILANO
DEPARTMENT OF ENERGY
DOCTORAL PROGRAMME IN ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY

NOVEL METHODS OF SCENARIO ANALYSIS FOR THE PROBABILISTIC RISK ASSESSMENT OF NUCLEAR WASTE STORAGE AND DISPOSAL FACILITIES

Doctoral Dissertation of:
Edoardo Tosoni

Supervisor:
Prof. Ahti Salo
Prof. Enrico Zio

Tutor:
Prof. Francesco Di Maio

The Chair of the Doctoral Program:
Prof. Vincenzo Dossena

2021 – XXXI

Supervising professors
Professor Ahti Salo, Aalto University, Finland
Professor Enrico Zio, Politecnico di Milano, Italy

Preliminary examiners
Karen E Jenni, PhD, U.S. Geological Survey, United States
Professor Marko Mäkelä, University of Turku, Finland

Opponent
Professor Man-Sung Yim, Korea Advanced Institute of Science and Technology, South Korea

Aalto University publication series
DOCTORAL DISSERTATIONS 104/2021

ISBN 978-952-64-0465-3 (printed)
ISBN 978-952-64-0466-0 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-64-0466-0

Unigrafia Oy
Helsinki 2021

Finland

Printed matter
4041-0619

Aalto University
Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Edoardo Tosoni

Name of the doctoral dissertation
Novel methods of scenario analysis for the probabilistic risk assessment of nuclear waste storage and disposal facilities

Publisher School of Science

Unit Department of Mathematics and Systems Analysis

Series Aalto University publication series DOCTORAL DISSERTATIONS 104/2021

Field of research Systems and Operations Research

Manuscript submitted 12 April 2021 **Date of the defence** 14 September 2021

Permission for public defence granted (date) 23 June 2021 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

The safety of nuclear waste management facilities is typically assessed by considering accident scenarios in which the containment function may be compromised. In some scenario analysis approaches, relatively few scenarios are built based on the available knowledge. Then, the containment performance of the facility and the resulting radiological impact is analyzed separately for each scenario. Alternatively, other approaches consider scenarios within a structured probabilistic safety assessment.

Probabilistic safety assessment systematically accounts for the aleatory uncertainty about the evolution of the nuclear waste management facility under a set of accident scenarios. Thus, the probabilities and impacts of these scenarios are aggregated into an estimate of the overall risk. The scarcity and imprecision of the data utilized in the safety assessment also involves epistemic uncertainty, as it is hard to assign precise values to event probabilities and other model parameters.

This dissertation addresses the modeling of uncertainties in estimating the risk of nuclear waste management facilities, and what this implies for the comprehensiveness of scenario analysis as a support to risk-informed decision making. Specifically, it is suggested that comprehensiveness is achieved when the uncertainty about risk is sufficiently small to assess conclusively whether the facility is safe or not.

The main challenges in the attainment of comprehensiveness are also identified, and novel methodologies for probabilistic scenario analysis are presented. In particular, Bayesian networks and probabilistic cross-impact analysis are developed to describe systemic dependencies. Epistemic uncertainties are characterized through probability distributions or regions of feasible values. The uncertainties are propagated to the risk estimate by using Monte Carlo simulation or solving optimization problems. Risk importance measures are introduced and calculated to identify which scenarios contribute most to the overall risk level. This offers relevant information for risk management decisions.

Keywords Risk assessment; Scenario analysis; Uncertainty; Bayesian networks

ISBN (printed) 978-952-64-0465-3 **ISBN (pdf)** 978-952-64-0466-0

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2021

Pages 181 **urn** http://urn.fi/URN:ISBN:978-952-64-0466-0

Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Edoardo Tosoni

Name of the doctoral dissertation
Novel methods of scenario analysis for the probabilistic risk assessment of nuclear waste storage and disposal facilities

Publisher School of Science

Unit Department of Mathematics and Systems Analysis

Series Aalto University publication series DOCTORAL DISSERTATIONS /

Field of research Systems and Operations Research

Language English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

L'analisi di sicurezza degli impianti per la gestione di rifiuti nucleari si fonda tipicamente su scenari in cui il corretto funzionamento delle barriere di contenimento può essere compromesso. Tra tali approcci, detti di analisi di scenario, alcuni considerano un limitato numero di scenari. In particolare, la funzione di contenimento e l'eventuale impatto radiologico dell'impianto sono analizzati separatamente per ognuno di questi scenari. In alternativa, altri approcchi all'analisi di scenario sono basati su più strutturati metodi probabilistici di analisi di rischio.

L'analisi di rischio probabilistica fornisce una caratterizzazione sistematica dell'incertezza aleatoria circa l'evoluzione dell'impianto in un insieme di scenari. Le probabilità e gli impatti di questi scenari sono infatti aggregati in una stima globale del rischio. Ad ogni modo, la scarsità e l'imprecisione dei dati a disposizione dell'analisi aggiungono incertezza epistemica, poiché è difficile valori puntuali a probabilità e altri parametri del modello di rischio.

La presente tesi affronta la descrizione delle incertezze nella stima del rischio degli impianti per la gestione di rifiuti nucleari, con particolare attenzione alle implicazioni per l'esaustività dell'analisi di sceanario come supporto al processo decisionale. In concreto, si propone di considerare l'analisi di scenario esaustiva quando l'incertezza circa il rischio è sufficientemente ridotta per concludere se l'impianto è sicuro o no.

La tesi discute inoltre le principali difficoltà nell'ottenere un'analisi di scenario esaustiva, e presenta delle innovative metodologie probabilistiche di analisi di scenario. Per esempio, le dipendenze tra le variabili del sistema sono caratterizzate tramite reti Bayesiane o matrici probabilistiche di interazione. Le incertezze epistemiche sono quantificate per mezzo di distribuzioni di probabilità o regioni di valori plausibili. Queste incertezze sono propagate dai parametri del modello alla stima del rischio utilizzando simulazioni Monte Carlo o risolvendo problemi di ottimizzazione. Come ulteriore supporto alle decisioni per la gestione del rischio, sono anche introdotti e calcolati alcuni indicatori di importanza al fine di riconoscere quali scenari contribuiscono maggiormente al livello totale di rischio.

Keywords Risk assessment; Scenario analysis; Uncertainty; Bayesian networks

ISBN (printed) **ISBN (pdf)**

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year**

Pages **urn** http://urn.fi/URN:ISBN:

Contents

Acknowledgements

My deepest gratitude goes to my Professors Ahti Salo and Enrico Zio. Had it not been for them, I would have never studied and practiced the most exciting discipline of risk analysis. I also wish to thank Doctor Karen E Jenni and Professor Marko Mäkelä for their appraisal of my thesis, and Professor Man-Sung Yim for letting me defend it as my official opponent.

I am also grateful to the all persons who guided me during my education. I thank my primary-school teachers Loredana Locatelli and Chiara Battocchio for leading my first steps into learning. I thank my middle-school teacher Giuseppina Ottonelli for planting my mindset of drawing schemes and finding connections between facts. I thank my high-school teachers Luisa Bagiotti, for transmitting her love for culture and knowledge, and Laura Miglino and Patrizia Demichelis, for explaining mathematics, physics, chemistry and geology in ways I will never forget.

Moving to my university years, I thank Professor Clelia Marchionna for her willingness to help on various matters at any time. I thank Professor Elio “Lello” Piazza for accepting to supervise my Bachelor thesis, my very first work on radioactive waste, and Professor Fabrizio Campi for his help with that. I warmly thank Professor Francesco Cadini for his daily instruction and supervision of my Master thesis. I also thank Doctor Laura Porzio for her support to the case study of this work. I thank Professor Francesco Di Maio for tutoring my doctoral studies, and Professor Piero Baraldi for the insightful discussions. I thank Doctor Suvi Karvonen for managing our project within the KYT2018 research program, and Doctor Joan Govaerts for hosting me and working together at the Belgian Centre of Nuclear Studies. I also wish to thank Professor Ullrika Sahlin and Doctor Marja Ylönen for our activities in the Society for Risk Analysis Europe.

My years in research brought many friends (who, as such, are mentioned without titles). I thank my friend Alessandro Mancuso for helping me since day 1 with the practicalities of being an emigrant to Finland, and for sharing the joys of it thereafter. I thank my friends Matteo Brunelli, Emanuele Ventura and Michele Urbani for the entertaining times together. I want to thank my friends Ellie Dillon, Fabricio Oliveira, Nikita Belyak and Lucas Condeixa. I thank my friends from the Systems Analysis Laboratory Antti Toppila, Anton Von Schantz, Vilma Virasjoki, Tuomas Lahtinen, Yrjänä Hynninen, Mikko Harju, Pekka Laitila and Heikki Puustinen. Among them, special thanks go to Juho Roponen for co-authoring one of this dissertation’s articles. I thank my friends from the LASAR lab at Politecnico di Milano Wei Wang, Federico Antonello, Mojtaba Hosseini and Dario Valcamonico.

The persons in my family and in my circle of friends outside academia have always been fundamental, also during my doctoral studies. I strongly hope each of them will always know how important they are, regardless of their explicit mention on this page.

List of Abbreviations

ARPA	Agenzia regionale per la protezione dell’ambiente
BN	Bayesian network
FEPs	Features, events and processes
GA	Genetic algorithm
RIMs	Risk importance measures

List of Publications

This doctoral dissertation consists of a summary and of the following publications, which are referred to in the text by their numerals

1. Tosoni, Edoardo; Salo, Ahti; Zio, Enrico. 2018. Scenario analysis for the safety assessment of nuclear waste repositories: a critical review. Risk Analysis, 38(4), 755-776.

2. Cadini, Francesco; Tosoni, Edoardo; Zio, Enrico. 2016. Modeling the release and transport of 90Sr radionuclides from a superficial nuclear storage facility. Stochastic Environmental Research and Risk Assessment, 30, 693-712.

3. Tosoni, Edoardo; Salo, Ahti; Govaerts, Joan; Zio, Enrico. 2019. Comprehensiveness of scenarios in the safety assessment of nuclear waste repositories. Reliability Engineering and System Safety, 188, 561-573.

3 bis. Tosoni, Edoardo; Salo, Ahti; Govaerts, Joan; Zio, Enrico. 2020. Definition of the data for comprehensiveness in scenario analysis of near-surface nuclear waste repositories. Data in Brief, 31, 105780.

4. Salo, Ahti; Tosoni, Edoardo; Roponen, Juho; Bunn, Derek. Using cross-impact analysis for probabilistic risk assessment. Manuscript, 25 pages. Submitted in April 2021.

5. Salo, Ahti; Tosoni, Edoardo; Zio, Enrico. Risk importance measures for scenarios in probabilistic risk assessment with Bayesian networks. Manuscript, 31 pages. Submitted in October 2019.

Author’s Contribution

Paper 1: Scenario analysis for the safety assessment of nuclear waste repositories: a critical review.
Under the guidance of Prof. Salo and Prof. Zio, Tosoni selected the references, carried out the literature review, analyzed the results, and identified the main challenges to address for scientific contribution. Tosoni wrote the paper under the supervision of Prof. Salo and Prof. Zio.

Paper 2: Modeling the release and transport of 90Sr radionuclides from a superficial nuclear storage facility.
The work was carried out for Tosoni’s M.Sc. thesis at Politecnico di Milano. Under the guidance of Prof. Zio and the instruction of Prof. Cadini, Tosoni designed the case study, developed and coded the contaminant-transport model, calibrated the model parameters, and performed the uncertainty analysis for risk assessment. Tosoni wrote the paper with Prof. Cadini.

Paper 3: Comprehensiveness of scenarios in the safety assessment of nuclear waste repositories.
Under the guidance of Prof. Salo and Prof. Zio, Tosoni developed and coded the methodology, designed the case study, and carried out numerical analyses with Dr. Govaerts. Tosoni wrote the paper under the supervision of Prof. Salo and Prof. Zio.

Paper 3 bis: Definition of the data for comprehensiveness in scenario analysis of near-surface nuclear waste repositories.
This paper reports and illustrates the data for the case study of Paper 3. In collaboration with Dr. Govaerts, Tosoni chose the model parameters, organized them in a system model, defined their probability distributions, and prepared the input for computer simulations. Tosoni wrote the paper under the supervision of Prof. Salo and Prof. Zio.

Paper 4: Using cross-impact analysis for probabilistic risk assessment.
Tosoni worked together with Prof. Salo and Roponen in defining novel probabilistic cross-impact ratios, designed the case study, and produced data for numerical analyses. Tosoni wrote the section on the case study.

Paper 5: Risk importance measures for scenarios in probabilistic risk assessment with Bayesian networks.
With the supervision of Prof. Zio, Tosoni supported Prof. Salo in establishing novel risk importance measures for scenarios and their analytical properties, defined the Risk Share measure, coded the optimization algorithms, designed the case studies, carried out numerical analyses, and summarized instructions for risk management. Tosoni took part in writing the paper.

The domain of possible is almost infinite, that of real is very limited, because, out of all possibilities, one and only one can transform into reality.

Friedrich Dürrenmatt, The execution of justice.

1. Introduction

1.1 Nuclear waste management

The production of nuclear energy creates hazardous radioactive waste. At present, the most credible disposal solution is underground burial (Chapman & McKinley, 1987). Nuclear waste of moderate radioactivity can be placed in near-surface repositories that sit at depths of few tens of meters (or even at the surface under a top cover). Highly radioactive waste, such as spent nuclear fuel, is to be put in deep-geological repositories deep underground. While there are several near-surface repositories around the world, the only deep one is the Waste Isolation Pilot Plant in the United States (which is a special case as it is restricted to military waste). Apart from the specific design, nuclear waste repositories are based on a multi-barrier concept for containing radionuclides (i.e., radioactive particles) inside the waste.

Before disposal, nuclear waste is temporarily stored in the nuclear power plants or other facilities. This is because it first needs to be refrigerated, or because there are no disposal solutions available.

Throughout storage and disposal, nuclear waste should be confined until its radioactivity has decayed to safe levels. Depending on the radionuclides in the waste inventory, this may take up to 10,000 or even 1,000,000 years. Due to barrier degradation, some radionuclides will still escape the facility before safe levels have been reached. After migrating through the environment and the food chain, these contaminants may reach humans and expose them to radiations.

Therefore, before a nuclear waste management facility is licensed for construction and operation, it is necessary to ensure that its radiological impact on the public will be as low as reasonably achievable. Towards this end, nuclear waste management agencies (hereafter represented as the risk assessor) conduct risk assessments that are reviewed by nuclear safety authorities.

1.2 Uncertainty, risk and decision making

The licensing of a safety-critical facility such as a nuclear waste repository is a decision on a system that does not exist yet. This decision cannot be informed by deterministic predictions, because they cannot fully capture the actual evolution of the system. Many of the deterministic mechanisms which govern the system evolution are in fact unobservable (Pearl & Verma, 1992). Thus, it is more useful to provide a risk estimate on the basis of the spectrum of possible events.

There are various definitions of risk and ways to quantify it (Society for Risk Analysis, 2018). In general, risk is an aggregation of likelihoods and impacts of the different possible outcomes of uncertainties. The estimation of these likelihoods through the characterization of uncertainty is a foundational element of risk analysis.

One instrument to characterize uncertainty is probability theory. Consider the anecdotal coin toss, for instance. Based on the history of tossed coins, one would state that the probabilities of the coin falling with heads or tails up are 50% each. Statements about the probability of an earthquake occurring at a given time and area cannot be as precise due to the rarity of earlier events, for instance.

Exact probability statements on the tossed coin are usually accompanied by the caveat that the coin should be well balanced. If there is no certainty that this is the case, one may abstain from stating what the probability of either face of the coin exactly is.

Against this background, it is customary in risk analysis to distinguish between two main types of uncertainty. On one hand, aleatory uncertainty is the randomness of an outcome (Fox & Ülkümen, 2011). In the example of the coin, this is about whether the face up will be heads or tails. On the other hand, epistemic uncertainty is the imprecision of the information (Fox & Ülkümen, 2011; Aven & Zio, 2011). This may cause the probabilities of the outcomes of the coin toss not to be known exactly.

As a rule, epistemic uncertainty can be reduced by acquiring additional information. For instance, a data-informed process may be carried out by tossing the coin many times until the frequencies of heads and tails converge to stable values (e.g., 50%-50%, or 60%-40%, 70%-30%, etc., if the coin is loaded). Aleatory uncertainty is commonly deemed irreducible, as the use of probabilities to model the uncertainty of an event is not a quantity that can be modified incrementally.

The boundary between aleatory and epistemic uncertainty is not clear-cut in the practice (Hora, 1996). An alternative view is a model-oriented interpretation (Der Kiureghian & Ditlevsen, 2009). Specifically, the distinction between the uncertainties would only make sense within the *model* of reality. Rather than labelling the uncertainty associated with each variable at the onset of the risk assessment, the risk assessor may first decide how to characterize each uncertainty, and then proceed with a categorization. For instance, uncertainty about the occurrence of an event can be characterized with a probability and considered as aleatory, whereas the uncertainty about this probability can be quantified through imprecise values and considered as epistemic.

Aleatory and epistemic uncertainties appear in the risk assessment of nuclear waste management facilities. As a result of the long lifetime of the waste, there is aleatory uncertainty about the evolution of the system formed by the facility and its surrounding environment. This system can be largely described through relevant physical, chemical (or even human) factors, collectively referred to as features, events and processes (FEPs). There is also uncertainty about the dependencies between the FEPs. These dependencies can be so complex that the state of the system cannot be straightforwardly determined based on the states of the FEPs (Society for Risk Analysis, 2018).

Epistemic uncertainty is instead represented by the imprecision of the information provided by the instruments utilized to study the nuclear waste management facility. For example, the migration of radionuclides through the barriers of a repository and the environment is typically simulated through models whose parameters are not precisely known. In probabilistic approaches, it is usually not possible to estimate probabilities precisely either.

In the presence of these uncertainties, the radiological impact of the facility can be assessed more appropriately through risk (e.g., the *expected value* of the dose rate to the public is

0.1 mSv/y, or the *probability* of the dose rate being more than 1 mSv/y is 5%) than through prediction (e.g., the dose rate *will be* 0.2 mSv/y). Concretely, the risk assessor should estimate the likelihood and radiological impact of a number of possible evolutions of the system. The results can be aggregated into a risk estimate which quantifies the expected dose rate to the public or the chances that this rate exceeds some predefined safety threshold.

The licensing of a nuclear waste management involves economical and political issues. From the viewpoint of safety, the facility can be approved if the risk estimate is lower than the acceptable risk limit. This limit should coincide with the risk level in the business-as-usual alternative in which the facility is not licensed (Borgonovo & Cillo, 2017).

The licensing decision, however, needs to be taken facing epistemic uncertainty. If the risk assessor describes the likelihoods and impacts of the evolution of the FEPs as distributions or intervals, then risk will be estimated as a distribution or interval as well. In case of overlap between the imprecise risk estimate and the risk limit, the results are not conclusive. Especially with Paper 3, this dissertation elaborates on the implications of epistemic uncertainty on the conclusiveness of risk assessment as a support to decision making.

1.3 Scenario analysis and comprehensiveness

A way of characterizing the aleatory uncertainty about the evolution of the system is scenario analysis (Leinonen, et al., 2021). An important quality of scenario analysis is *comprehensiveness*. This term indicates the exhaustive coverage of the spectrum of possible evolutions of the system. Especially with regard to nuclear waste management, though, the scenario analysis literature does not specify what it practically means and how it can be evaluated (see Paper 1). Thus, the link between comprehensiveness and the ability to inform risk-based decisions conclusively is not fully established. This has created tensions about which approach should be adopted for achieving comprehensiveness in scenario analysis (see Paper 1).

In the pluralistic approach, risk assessors formulate a limited number of scenarios based on different assumptions about the evolution of the FEPs. Specifically, each scenario depicts a more or less severe impairment of the safety functions of the nuclear waste management facility. The impact of each scenario is usually assessed by computer simulation and checked against a safety threshold. There is no quantification of how likely the scenarios are, because scenario probabilities are not employed. Consequently, the scenario impacts are not aggregated, but presented separately from each other in the results.

Probabilistic approaches include a wide family of methods, which rely on building a probability space of scenarios. Each elementary event of this probability space is a joint realization of the FEPs and represents a specific evolution of the system. Any set of such elementary events (i.e., an event in the probability space) constitutes a scenario. Probabilistic approaches are characterized by the definition of a probability distribution over the sample space of elementary events and, hence, over the scenarios. As in the pluralistic approach, the scenario impacts can be quantified with computer simulations. However, the key difference is that these impacts are weighted by the scenario probabilities, and then aggregated into a single risk estimate.

Advocates of the pluralistic approach object that the probabilistic approach lacks transparency, because the overall risk estimate does not explicitly quantify the contribution of each scenario (Chapman, et al., 1995). They also argue that the uncertainty of having overlooked fundamental FEPs is so large that it is meaningless to use probabilities for characterizing the aleatory uncertainty about the limited system of the identified FEPs.

Criticisms are mutual, though. According to probabilistic researchers and practitioners, displaying few pluralistic scenarios does not permit a thorough quantification of risk. For instance, if one or more scenarios exhibit violations of the safety threshold, it can be claimed that these scenarios are so unlikely that they can be neglected (Sumerling & Thompson, 1992). Nevertheless, with no support of probabilities, it is difficult to overrule scenarios, no matter how unrealistic (Mallants & Chapman, 2020). Even if there is no violation among the scenarios, the nonmonotonicity of the radiological impact makes it hard to demonstrate that a new scenario would not (Goodwin, et al., 1994).

In summary, choosing how to conduct scenario analysis is not trivial. Specifically, no approach offers a fully convincing solution to evaluate comprehensiveness. This may have been one of the reasons why safety authorities have been slow to reach conclusions on the risk acceptability of nuclear waste management facilities. This dissertation aims at combining the strengths of current approaches to overcome their weaknesses, with the goal of improving the systematization of scenario analysis towards the achievement of comprehensiveness.

The focus of the dissertation is on nuclear waste management but, apart from specific references to the related phenomena, the findings can be arguably extended to scenario analysis for risk assessment at large. In this regard, the term “FEPs” may be replaced in the discussion by the more generic expression “system factors”.

2. Methodological background

The papers of this dissertation build on several methodologies which are briefly covered in this section. Some of the papers use these methodologies as such, while others advance the state-of-the-art.

2.1 Simulation

Nuclear waste disposal is based on the principle of concentrate-and-confine, meaning that waste is protected by multiple barriers organized in a Russian-doll structure (Chapman & McKinley, 1987). In near-surface repositories, these barriers consist of concrete containers of increasing dimensions. Deep geological repositories are designed with the KBS-3 technology (Montonen, et al., 2020), which consists of a copper canister surrounded by a buffer made of bentonite (i.e., a highly compacted clay). Before final disposal, nuclear waste is stored in the refrigeration pools of auxiliary facilities.

Nuclear waste is characterized, in particular, by its radionuclides. These are radioactive isotopes of elements like strontium, iodine and plutonium, among others. Radionuclides can escape through fractures or other defects in the containment barriers. Such defects may be present since the construction phase or they may arise during the facility's lifetime. Barrier degradation is also caused by stressors such as mechanical strains, corrosion and erosion.

The main driver for the release and subsequent transport of radionuclides is water. Except for the Yucca Mountain project at a desertic flatland in Nevada, deep geological repositories can be assumed to lie in the saturated zone. If water completely fills the voids in the soil, the repository barriers can be exposed to aggressive chemical substances. In near-surface repositories, rainfall can seep through the top cover, get in contact with the containment barriers and foster their degradation. Once mobilized, the radioactive particles start migrating through the barriers and into the environment.

A number of hydrogeological variables affect the migration of radionuclides, such as the velocity of water and the interaction between the contaminant and the solid matrix of the transport medium. In risk assessment, these phenomena need to be simulated to estimate the radionuclide concentration at locations where they may be ingested or inhaled by humans. Several experimental studies have been conducted with this aim (Savage, et al., 1987; Rochelle, et al., 1994). Yet, the results of these studies cannot be readily extended to field-scale conditions. Most risk assessments therefore rely on the mathematical modelling of physical and chemical phenomena.

The advection-dispersion equation (ADE) (Bear, 1979; Bear & Cheng, 2010) explains how the concentration of a contaminant varies in space and time as an effect of its transfer with water, diffusive Brownian motion, turbulence, adsorption, radioactive decay, among others. In most applications, the heterogeneity of the transport medium involves complex boundary conditions that make it difficult to derive an analytical solution.

Alternatives to analytical solutions of the ADE include numerical methods, compartment models and particle-tracking algorithms. As an example of the latter group, the Kolmogorov-Dimitrev particle-tracking algorithm (Marseguerra & Zio, 1997; Giacobbo & Patelli, 2008; Cadini, et al., 2010 (a); Cadini, et al., 2010 (b); Cadini, et al., 2012; Cadini, et al., 2013) treats the spatial domain as a discrete set of cells so that the transition of each contaminant particle from one cell to another is modeled as an exponential process. Computational solutions have been implemented in computer codes, some of which are embedded in commercial tools like MT3DMS (Khayyun, 2018), GoldSim (Lee & Hwang, 2009) and COMSOL Multiphysics (Seetharam, et al., 2012).

While these tools cover the transport of radionuclides, disposal systems are so complex that additional simulation models may be needed. For instance, in areas prone to glaciation, mechanical displacements in the geological formations under the pressure of the ice sheet may require dedicated modelling (Hutri & Antikainen, 2002). Thus, nuclear waste management facilities are often studied by using several simulation models rather than a single tool that covers all relevant phenomena.

Conceptually, a simulation model is a function between the values of input output variables, where there can be uncertainty about which values of the input variables are more likely. Once these values are fixed, the values of the output variables follow.

2.2 Bayesian networks

The study of complex systems (like facilities of nuclear waste management are) should build on a representation of all the system factors and dependencies thereof. *Bayesian networks* (BN) offer this kind of representation (Jensen, 2001; Pearl & Russell, 2003). For example, the BN of Figure 1 (Pearl & Russell, 2003) shows a system where the ground might get slippery. As it can be seen, the system factors are modeled as nodes, whose dependencies are indicated by directed arcs.

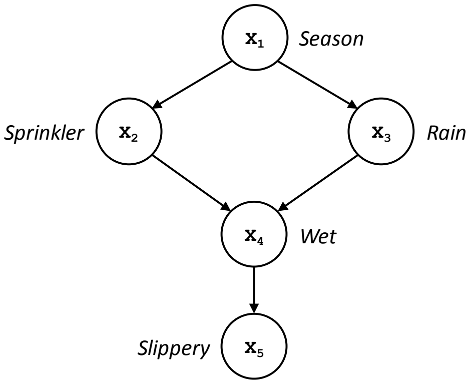

Figure 1. Bayesian network with the probabilistic dependencies in a system where the ground might get slippery (Pearl & Russell, 2003).

A BN contains independent nodes (i.e., Season in Figure 1) and nodes which depend on others as indicated by the arcs (all the remaining ones in Figure 1). Each dependent node is referred to as *child*, whereby its immediate predecessors in the BN are its *parents*. For example (Figure 1), Sprinkler and Rain are the parents of Wet.

Each node corresponds to a random variable with discrete states, which, in Figure 1, may correspond to the seasons of the year, to the sprinkler being on or off, to rain being falling or not, etc. The performance of the system may be assessed through the states of a target node, e.g., by evaluating whether the ground is slippery or not in Figure 1.

In nuclear waste management, the system factors (i.e., the FEPs) usually correspond to variables that are not inherently discrete. In this case, as also customary in other fields (Di Maio, et al., 2015; Mancuso, et al., 2017), it is possible to proceed with the discretization of continuous ranges (Uusitalo, 2007). For instance, the chloride concentration can be in a low, medium or high state depending on it belonging to the range [0, 23 g/l), [23 g/l, 46 g/l) or [46 g/l, 70 g/l], respectively.

The parameters of BNs are probabilities. The state probabilities for a dependent node are conditioned on the states of its parents. For independent nodes, in turn, the state probabilities are marginal. If states are obtained by discretization, there is an approximation error due to the loss of information about how the probability density function spreads within each of the variable's discretization ranges (Zwirglmaier & Straub, 2016).

BNs can be used to calculate the probability of any set of states. By the *global semantics* (Pearl & Russell, 2003) of BNs, the joint probability of the states x_1, x_2, x_3, x_4, x_5 of the five nodes in Figure 1 is

$$p(x_1, x_2, x_3, x_4, x_5) = p(x_1)\, p(x_2|x_1)\, p(x_3|x_1)\, p(x_4|x_2, x_3)\, p(x_5|x_4)\,.$$

This factorization is permitted by the Markov property of BNs, that is, by the fact that the probability of a node state does not depend on any previous predecessor once the states of its parents are given.

BNs can also be used for probabilistic inference, that is, for calculating the probability of one set of nodes' states conditioned on new evidence about the states of other nodes. For example, one may ask about the probability that the sprinkler is on, given that it is summer and the ground is wet. In large BNs, the computation of inferential queries can be so burdensome that approximation algorithms may be needed (Pearl, 1987).

In some applications the structure of the BN is defined *a priori*, whereas in others the BN is the outcome of a data-analysis procedure. In the first case, analysts can use their expertise to draw arcs that represent dependencies between the system factors. Then, the BN is filled in with probabilities based on data such as historical observations, computer simulations or, again, expert beliefs. In the second case, large amounts of data are processed to determine which structure of the BN gives the best fit between probabilities and observed frequencies (Uusitalo, 2007).

This dissertation focuses on the first situation, where the BN is based on prior expert knowledge. Also, in keeping with earlier works (Käki, et al., 2015; Tolo, et al., 2016), BNs are here used for scenario-based risk assessment. Specifically, scenarios are defined as combinations of states of the nodes, and risk is estimated as the probability of the target node's state that represents unacceptable consequences (e.g., when "Slippery" is "yes"). This probability can also be reproduced as expected disutility (the loss-oriented version of utility) by setting the disutility of the unacceptable state of the target node to 100% and that of the acceptable ones to 0.

2.3 Imprecise information

The probabilities in the BN can be uncertain. In other words, the scarcity and imprecision of data may not warrant sufficient evidence to assign exact probability values to them. To characterize this epistemic uncertainty - also in other system models like fault trees (Toppila & Salo, 2013) – probability bounds can be employed. Then, any function of these probabilities will also be interval-valued (Tolo, et al., 2017 (a)), including expected (dis)utilities and risk estimates. BNs with interval-valued probabilities may also be referred to as credal networks (Mancuso, et al., 2017) or enhanced BNs (Tolo, et al., 2017 (b)).

One could argue that bounds should be "hard" extremes between which the probability value lies with certainty. In the engineering practice, it is common to employ confidence intervals based on the frequency with which the event of interest has been observed (Toppila & Salo, 2013). Still, because they can stem from unbounded distributions like the Gaussian ones, confidence intervals for probabilities pose truncation issues.

At the juncture between frequentist and Bayesian approaches, one may start with a prior belief about the event probability and then update this into a posterior estimate based on how many times the event has occurred. If the event is modeled as the outcome of a Bernoulli process, such posterior is the expected value of a Beta distribution. However, unless there are strong reasons for utilizing a point value, uncertainty about the prior needs to be characterized as well.

This is the goal of the Imprecise Beta Model (Walley, 1991), which admits all priors between 0 and 1. This representation of full ignorance about the prior can be reasonable when studying systems like nuclear waste management facilities (especially deep geological repositories). The model provides both a lower and an upper Beta distribution for the posterior, which correspond to the prior being 0 and 1, respectively, and which encompass all Beta distributions that could have been obtained had the prior been fixed. While these bounding distributions already characterize epistemic uncertainty, they also make it possible to estimate a probability interval with the requisite level of *credibility* (Walley, 1996). This is analogous to confidence, but it does not bear the statistical interpretation of quantifying the chances that the interval contains the actual probability value.

The propagation of the epistemic uncertainty from the probabilities to the risk estimate is a crucial but challenging task (Wei, et al., 2021). In this regard, unless bounds correspond to hard extremes, the propagation of probability bounds can be questioned for lack of statistical guarantees (be it in terms of confidence or credibility) about the resulting interval for risk, or any other function of the probabilities (Ferson, et al., 2013). Therefore, researchers have suggested the propagation of *confidence structures* (Balch, 2012; Ferson, et al., 2013). A confidence structure consists of two distributions which span all possible distributions for a given probability value. Under specific conditions (Ferson, et al., 2013), confidence structures coincide with the lower and upper distributions in the Imprecise Beta Model.

The attractiveness of this approach is that there is no loss of information during the propagation, and that bounding distributions can be obtained for the risk estimate, too. At present, there are open challenges in propagating confidence structures of dependent variables (Beer, et al., 2013). This is the case with the state probabilities which must sum up to 1. While confidence structures surely represent a promising area of improvement, this dissertation focuses on the propagation of intervals.

The approach adopted for the Waste Isolation Pilot Plant and Yucca Mountain repositories (United States) is also notable. First, probability distributions are defined over the values of the system factors. Then, further distributions are defined for the parameters (means, variances, etc.) of the probability distributions of the system factors' values.

Lastly, probabilities are not the only quantities affected by epistemic uncertainty. There are also parameters which represent the physical and chemical variables in simulation models. It is customary to characterize these variables through probability distributions. Section 4.2 elaborates on the different situations in which these variables are modeled as system factors through which to generate scenarios (wherefore their uncertainty should be considered as aleatory) or simply treated as model parameters (whereby their uncertainty is epistemic).

2.4 Cross-impact analysis

Scenarios can be defined as combinations of discrete states of the system factors. Thus, when considering all possible combinations of states of all factors, the number of scenarios grows exponentially. If there are two factors with three states each, there are $3^2 = 9$ scenarios. With five factors the number of scenarios is already $3^5 = 243$.

This can prove computationally challenging when seeking to derive risk estimates based on the assignment of probabilities to the scenarios. Even when scenarios are analyzed qualitatively by panels of experts, without any probabilistic characterization, the cognitive strain of handling a very large number of scenarios would become overwhelming.

In qualitatively oriented approaches, it is common to exclude scenarios which contain states that are too unlikely to occur together. To enforce this criterion, it is necessary to assess how the system factors are interdependent, taking into account synergetic or antagonistic effects which increase or decrease, respectively, the likelihood that given pairs of states for the system factors occur jointly.

This is the purpose of *cross-impact analysis* (Asan & Asan, 2007). One of its developments relies on the elicitation of cross-impact terms (Weimer-Jehle, 2006; Weimer-Jehle, 2008). Specifically, the cross-impact term associated with the influence of the state x of system factor X on the state y of system factor Y is the answer to the following question: "Assuming that system factor X is in state x, by how much is the occurrence of the state y of system factor Y promoted or hindered?". This statement is based on integer scales ranging, e.g., from -3 to +3 so that 0 stands for independence, whereas negative and positive values indicate that the influence is of hindrance or promotion, respectively (Weimer-Jehle, 2006).

Cross-impact terms can be employed to screen out scenarios. The state of each system factor can be assigned a score which depends on the sum of the influences from the states of the other factors, as quantified by the corresponding cross-impact terms. This score (or cross-impact *balance*) can be taken as a measure of how compatible this state is with the other ones in the scenario. A scenario is deemed *consistent* if none of these scores can be improved by swapping the state of the system factor in question (i.e., each factor appears in the scenario with a state which is the "most promoted" by the states of the other factors in the scenario). Finally, inconsistent scenarios could be excluded from further consideration. This approach can be very efficient in reducing the number of scenarios. There are examples in which as few as 3 out of 324 scenarios have been retained on the grounds of consistency (Weimer-Jehle, 2006).

The straightforward dismissal of scenarios can be problematic in risk assessment. The semi-quantitative scale for assessing the cross-impact balances has no physical interpretation, nor a link to the joint probability of the system factors' states. Even conjecturing a relation between inconsistency and extremely low probability, the exclusion of scenarios from the calculation is likely to lead to the underestimation of risk.

2.5 Risk importance measures

Apart from knowing the overall level of risk in a system, it is important to understand which system factors can impair the overall safety performance most. The risk estimate as such does not contain enough information to drive actions of risk management aimed at reducing risk, or at preventing its rise to unacceptable levels.

Such information is provided by *risk importance measures* (Zio, 2011). Dating back to the 1970s, such measures have been introduced to identify the components (pumps, valves, generators, etc.) whose failure could lead to the largest increase in the failure probability of a technical system, or whose failure should be prevented with the highest priority to reduce the overall failure probability (Barlow & Proschan, 1975; Fussell, 1975; Natvig, 1979). There are further measures which consider incremental changes in the component's failure probability rather than its complete failure (Birnbaum, 1969; Borgonovo & Apostolakis, 2001).

Traditional risk importance measures are tailored to system models like fault trees, in which components have Boolean states ("functioning" and "failed"), and dependencies can be represented by logical gates. There have been some extensions to multiple states of system components (Zio & Podofillini, 2003; Levitin, et al., 2003) and to probabilistic dependencies (Noroozian, et al., 2018). Still, these approaches require mapping the states of each component to the categories of functioning or failed.

The labelling of states as "functioning" and "failed" has limitations, for instance, in the analysis of noncoherent systems (Beeson & Andrews, 2003; Borgonovo, 2010) where one or more components may need to function to cause the system failure (for example because the effects of their individual failures would cancel out).

Moreover, there are systems whose factors cannot be modeled as components that function or fail. This holds for complex systems (e.g., nuclear waste management facilities) where the interactions between the system factors (i.e., the FEPs) preclude any *ex ante* declaration of failure states. For example, in deep geological repositories, high chloride concentrations can cause the corrosion of the copper overpack of the canisters which contain the spent nuclear fuel (Posiva Oy, 2012), whereas low concentrations can promote the erosion of the bentonite buffer which protects the canister. It is the combination of the actual concentration with low or high groundwater flows that determines which level contributes more to the overall risk. Before quantitative analyses of these consequences (e.g., by computer simulation), it is not obvious which states are riskiest.

3. Contributions of the dissertation

This dissertation addresses the challenges in attaining comprehensiveness in scenario analysis for nuclear waste management facilities. Specifically, it presents novel probabilistic methodologies for scenario-based risk assessment. Based on the findings from the application of these methodologies, three main suggestions are given (and discussed in Section 4), namely i) modeling systemic dependencies, ii) characterizing uncertainty and iii) ensuring transparency. Figure 2 illustrates the flow of the dissertation from the identification of the challenges to the suggestions for scenario analysis, and also indicates the scope of the papers included in the dissertation. The papers are summarized in Table 1, and presented at more depth in sections 3.1 through 3.6.

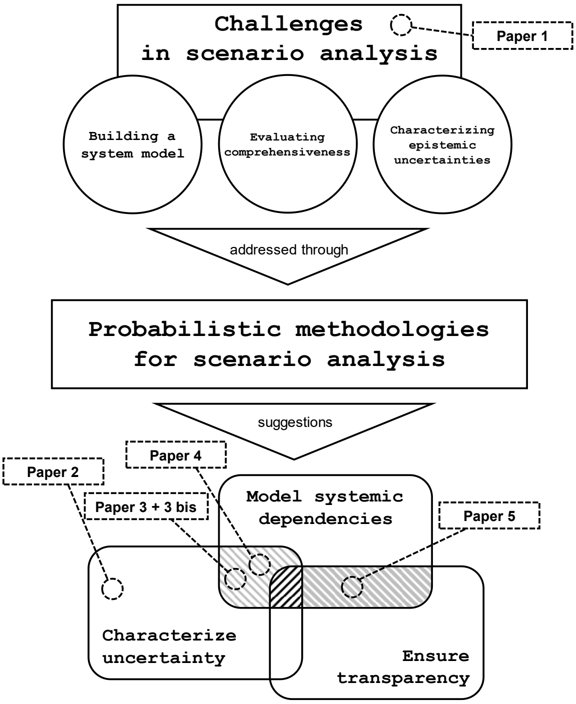

Figure 2. Logical thread of the dissertation and scope of the papers.

Paper 1 identifies three main methodological challenges in scenario analysis. First, it is important to construct a system model of the facility and the surrounding environment to display all the significant FEPs and their dependencies. Second, comprehensiveness must be evaluated based on a general and widely recognized criterion instead of approach-dependent interpretations. Third, it is necessary to characterize several epistemic uncertainties (e.g., about probability and parameter values) which aggravate the two previous challenges.

Paper 2 tackles a case of groundwater contamination at the facility of Saluggia (Italy), where spent nuclear fuel used to be stored in water pools. Specifically, it presents a contaminant-transport model for estimating the time-dependent concentration of radionuclides at a point of interest. It also characterizes the uncertainties about the model parameters in the simulations of the physical and chemical phenomena that affect a nuclear waste management facility and its surrounding environment. It is shown that, due to these epistemic uncertainties, the radiological impact of the facility cannot be estimated deterministically even if there is no aleatory uncertainty about which scenario will occur.

In Paper 3, a BN is adopted as a system model where nodes correspond to the FEPs and directed arcs represent the probabilistic dependencies between them. The probabilities of the FEP states can be obtained from computer simulations and expert beliefs. Epistemic uncertainty about the probabilities is characterized with feasible probability regions rather than point values. These feasible regions are propagated by multilinear programming to estimate the lower and upper bounds of the interval-valued radiological risk. The novel adaptive Bayesian sampling algorithm helps prioritize which scenarios to simulate for reducing residual uncertainty, that is, the width of the risk interval. In keeping with a generalized interpretation presented in this paper, comprehensiveness is achieved in probabilistic approaches if the risk interval (i.e., the range of values between two extremes or two quantiles of a distribution) does not overlap the predefined risk limit (because it is possible to state conclusively whether risk is acceptably low or excessively high). This probabilistic methodology is applied to the nuclear waste repository planned for the site of Dessel (Belgium). The results suggest that the available data are not sufficient for the attainment of comprehensiveness. Paper 3 bis is a data article that illustrates the input for the case study of Paper 3.

Paper 4 tackles the same case study, but without using BNs and their predetermined structure of dependencies between the FEPs. Rather, nondirected dependencies between pairs of FEP states are characterized by *probabilistic cross-impact ratios*. Epistemic uncertainty is quantified through bounds to these ratios and to the marginal probabilities of the FEP states. This approach requires the corresponding risk interval to be calculated with nonlinear-programming solvers. Results emphasize that ignoring systemic dependencies can lead to considerable risk underestimates.

Finally, Paper 5 deals with transparency in scenario analysis. Estimating the overall risk does help assess safety, but is does not in fact identify which scenarios are riskiest in terms of impact and/or probability of occurring. Insights in this respect can be gained through risk importance measures. Nevertheless, traditional risk importance measures focus on the failure of individual system components, a notion which is incompatible with complex systems like nuclear waste repositories. Hence, novel risk measures are defined so that they refer to *scenarios* rather than to system components. Two case studies of literature are revisited, where the new measures help identify which scenarios contribute most to the overall risk and/or have the largest impact if they occur.

Table 1. Research objectives, methods and key takeaways from the papers in the dissertation.

Paper	Research objective	Methods					Key takeaways
		Simulation	Bayesian networks	Imprecise information	Cross-impact analysis	Risk importance measures	
1	Identifying challenges in scenario analysis	-	-	-	-	-	Build a system model, find a general interpretation of comprehensiveness, characterize epistemic uncertainties.
2	Characterizing epistemic uncertainty about model parameters	■	-	■	-	-	Even without aleatory uncertainty about the scenarios, epistemic uncertainty prevents deterministic prediction.
3 + 3 bis	Evaluating comprehensiveness	■	■	■	-	-	To evaluate comprehensiveness, quantify residual uncertainty about risk. Favor probabilistic over pluralistic approaches.
4	Quantifying systemic dependencies	-	-	■	■	-	Quantify systemic dependencies, e.g., with probabilistic cross-impact analysis. Ignoring dependencies can lead to risk underestimation.
5	Identifying the riskiest scenarios	-	■	-	-	■	In complex systems, resort to risk importance measures for scenarios to inform risk management.

3.1 Paper 1

This paper reviews the literature on the safety assessments of fourteen nuclear waste repositories worldwide as well as about scenario analysis at large. Specifically, it discusses key aspects of scenario analysis, including the interpretations of comprehensiveness, uncertainties and the alternative approaches to conduct scenario analysis. Finally, it identifies challenges for methodological contributions.

The first step in scenario analysis is the identification of the factors that are relevant for describing the system. In nuclear waste management, these factors are called features, events and processes (FEPs). The second step is to recognize all systemic dependencies between the FEPs. This step can be supported by a *system model*, i.e., a conceptual representation of the disposal system as a set of FEPs and dependencies thereof. In a further step, scenarios are generated as specific evolutions of the FEPs and, hence, of the system. Taken together, these three steps constitute scenario development. Subsequently, in consequence analysis, the scenario impacts are quantified, usually by way of computer simulation.

Completeness in scenario analysis is attained if all possible FEPs and scenarios are identified and analyzed. This is deemed unachievable for both cognitive and computational reasons (Chapman, et al., 1995). In FEP identification, there is no way of ensuring that risk assessors (or experts on their behalf) think of all conceivable factors that may affect the system. In scenario generation and consequence analysis, it is not possible to cover the infinite number of possible evolutions of the system.

More reasonably, scenario analysis should therefore aim to ensure *comprehensiveness*. In FEP identification, comprehensiveness requires that all FEPs which can *significantly* affect the system be identified. In scenario generation, there is no widely acknowledged definition of comprehensiveness, and thus different approach-dependent interpretations have prevailed.

Even though comprehensiveness in FEP identification is clear, it is less straightforward to evaluate it. Hence, the knowledge accumulated by experts in decades of risk assessments of nuclear waste repositories is currently the most reliable way to produce comprehensive lists of FEPs. This dissertation seeks to resolve some of the ambiguity about comprehensiveness in scenario generation and to develop systematic methodologies to pursue it.

Other uncertainties than that about the evolution of the system also make it hard to achieve comprehensiveness. One is the uncertainty of not having identified all significant FEPs. There is also uncertainty about the dependencies between the FEPs. The simulation models utilized for analyzing the scenarios are affected by uncertainty about the validity of their underlying assumptions. If multiple models are judged valid with regard to a given phenomenon, there is uncertainty about which of these models should be employed. Simulation models also contain parameters whose values may be uncertain. In probabilistic approaches, the latter consideration also extends to probability values.

The approaches to scenario analysis differ in how scenarios are generated to characterize the uncertainty about the system evolution. The pluralistic approach relies on expert judgment to formulate a relatively small set of scenarios which represent different assumptions about the FEPs and the evolution of the system. The radiological risk is assessed by comparing the scenario impacts with a safety threshold.

The probabilistic approach (an expression which includes a family of techniques) builds on a probability space in which i) each elementary event is constituted by a specific joint realization of the FEPs (i.e., a specific evolution of the system), ii) a probability distribution is defined over this sample space of elementary events, and iii) a scenario is an event, namely a set of elementary events. In the risk assessments of the Waste Isolation Pilot Plant (WIPP) and the Yucca Mountain repositories (United States), the exploration of these scenarios is carried out by repeatedly sampling and simulating FEP realizations from the probability space. The goal is to estimate risk as the expected radiological impact (to be checked against the safety threshold), and/or the probability that the safety threshold will be violated during the lifetime of the repository.

These two approaches interpret scenarios differently. In the pluralistic approach, a scenario is an array of assumptions without probabilities. In the probabilistic approach, a scenario is an event in a probability space. As such, it is a set of "similar" elementary events which are characterized by the same feature (e.g., the occurrence of an earthquake) whose realization is different in each of them (e.g., timing and magnitude of the earthquake).

In the WIPP and Yucca Mountain assessments, for instance, scenarios are characterized by disruptive events like inadvertent drillings of the repository barriers (Galson, et al., 2000), earthquakes, volcanic eruptions or waste-package failures (Rechard, et al., 2014). These rare events are treated as independent from each other, which is reasonable in this case. This has reduced the emphasis on systemic dependencies, to the extent that neither of these probabilistic assessments includes a system model.

In contrast, system models are found in the vast majority of the assessments which follow a pluralistic approach. The explanation is that displaying all dependencies between the FEPs helps make coherent assumptions when formulating scenarios by expert judgment, as opposed to building a mathematical structure such as a probability space.

The fundamental differences between approaches to scenario analysis also stem from alternative views on comprehensiveness. In the pluralistic approach, comprehensiveness is interpreted as *representativeness*, because the scenarios are intended to be representative, illustrative, depictions of the possible evolutions of the system. In the probabilistic approaches, comprehensiveness refers to the thorough coverage of the probability space in which scenarios are generated. In the American assessments above, this coverage is sought through a statistically significant size of the Monte Carlo sample.

Against this backdrop, this paper identifies the following challenges for scenario analysis: building a system model; evaluating comprehensiveness; characterizing epistemic uncertainties. These challenges are targeted in the remainder of the dissertation, but this paper already provides some suggestions.

For instance, systems models help show why some assessments focus on few specific FEPs. Assume, for example, that the dependence of one set of FEPs on another set of independent FEPs is fully described by a deterministic simulation model. It would then be possible to generate scenarios based on the realizations of the independent FEPs only, whereby the evolution of the other FEPs would be uniquely implied by the simulations. Here, the system model would highlight the deterministic relation between the two sets of FEPs, thus justifying the exclusion of the dependent set from the generation of scenarios.

The challenge of evaluating comprehensiveness also related to the lack of a widely acknowledged definition. This has indirectly encouraged the subjective interpretations in the current approaches to scenario analysis. In keeping with the generalized interpretation proposed in Paper 3, it is suggested that comprehensiveness is achieved when the results of the risk assessment are conclusive, i.e., the introduction of improved information about the scenarios cannot revert the conclusions on the safety of the nuclear management facility.

The attainment of comprehensiveness calls for the characterization of epistemic uncertainties. Yet, is hard to quantify the uncertainty that significant FEPs are missing from the assessment (in other words, that the FEP list is not comprehensive). The same consideration holds for the uncertainty about having identified all FEP dependencies. Instead, the uncertainty about the magnitude of these dependencies can be quantified through imprecise values (say, intervals) of the parameters through which they are modeled (be it conditional probabilities or cross-impact ratios as in Paper 3 and Paper 4, respectively). The characterization of uncertainties concerning the validity of model assumptions is more controversial, because risk assessors may feel ill-at-ease quantifying their belief that a model is correct (or that is more correct than others). Finally, the uncertainty about the value of model parameters can be characterized with probability distributions (see Paper 2). In probabilistic approaches, scenario probabilities are also parameters, but there is a variety of techniques that can be applied to quantify their uncertainty (see Paper 3).

3.2 Paper 2

The Eurex research facility at Saluggia (Italy) used to be a temporary storage solution for spent nuclear fuel. Nevertheless, in 2004, the regional environmental agency ARPA detected traces of ^{90}Sr (a radioactive isotope of strontium) underneath one of the pools which contained the spent-fuel bars. The pool was then emptied in 2008, but ARPA's monitoring campaign between 2006 and 2014 kept revealing some groundwater concentration of ^{90}Sr at a measurement point a few meters from the pool. Although the contamination was limited to shallow depths and within the plant boundaries, the presence of the local aqueduct pumps downstream of the facility with respect to the main groundwater flow called for an assessment of the radiological risk for the public.

To support such risk assessment, this paper presents a simulation model which reproduces the release and transport of ^{90}Sr in groundwater. In this case, rather than generating different scenarios, the goal is to simulate the known chain of events that have led to the contamination.

The model consists of two modules connected in cascade. In the first module, the radionuclide release is modeled as a continuous discharge from the cracked bottom of the pool between 2004 and 2008. Subsequently, a Kolmogorov-Dimitrev particle-tracking (KDPT) algorithm (Marseguerra & Zio, 1997; Giacobbo & Patelli, 2008; Cadini, et al., 2010 (a); Cadini, et al., 2010 (b); Cadini, et al., 2012; Cadini, et al., 2013) simulates the migration of radionuclides under stationary hydrogeological conditions across both the unsaturated zone and the saturated aquifer. The second module post-processes the output of the first one through a semi-empirical formula that implements the observed correlation between the concentration of ^{90}Sr and the oscillating depth of the water table (i.e., the interface between the unsaturated and saturated zone in groundwater). The final outcome of the model is the time-dependent ^{90}Sr concentration at the point of interest. This model represents a novel application of the KDPT algorithm to the unsaturated zone of a field-scale problem.

The model is calibrated by estimating the value of its six key parameters, namely four contaminant-transport variables from the first module and two coefficients in the formula of the second module. In particular, a genetic algorithm (GA) (Goldberg, 1989) determines the parameter values that minimize the error between the model outcome and the ^{90}Sr concentrations observed by ARPA at the monitoring point next to the Eurex pool.

Although the GA provides point parameter values, these are actually affected by various epistemic uncertainties. One is the imprecision about the concentrations based on which the error is minimized: on one hand, those simulated by the model are subject to the Monte Carlo error underlying the KDPT algorithm (Echard, et al., 2011); on the other hand, the observed ones (used for calibration) are prone to measurement errors. Another uncertainty is the lack of guarantees that the GA has found the global minimum of the error. For this reason, point parameter values are rejected in favour of reasonably defined probability distributions (e.g., Gaussian, Poisson and uniform).

These distributions are propagated through a crude Monte Carlo procedure in which i) realizations are sampled for the parameter values, ii) a simulation is run with these values as input to compute the time-dependent ^{90}Sr concentration, iii) the corresponding dose rate to the public is computed by way of the expression recommended by the International Commission on Radiological Protection (ICRP, 2012), and iii) the previous steps are iterated 1,000 times.

Risk is therefore assessed as the time-dependent probability of violating the predefined safety threshold on the dose rate (as customary in the safety assessment of nuclear waste management facilities, such threshold is taken to be a fraction of the regulatory limit). Specifically, for each time instant, this violation probability is estimated as the share of simulations in which the threshold is breached. The tasks from model calibration to uncertainty propagation are repeated by using different subsets of the dataset of observed ^{90}Sr concentrations, showing a satisfactory robustness of the assessment once six out of eight years of observations are included.

In summary, this study constitutes a "degenerate" scenario analysis where the attention is entirely put on a single chain of events that is known to have happened. Consequently, the aleatory uncertainty about what scenario will occur is ruled out. Yet, there are epistemic uncertainties about the values of the parameters in the simulation model which is used for reproducing the aforementioned events. These uncertainties impede a deterministic prediction of the radiological impact of the nuclear waste management facility, which must be instead assessed in terms of risk.

3.3 Paper 3

Because reaching completeness in scenario analysis is impossible, it is, strictly speaking, impossible to estimate risk precisely. In other words, scenario analysis inevitably leaves some *residual uncertainty* about the risk estimate.

Against this background, this paper posits that comprehensiveness is achieved if residual uncertainty is small enough to assess conclusively whether the nuclear waste management facility is safe or not.

The quantification of this residual uncertainty is crucial for evaluating comprehensiveness. As shown in this paper, residual uncertainty can be best quantified by probabilistic approaches, because they make it possible to estimate a lower and an upper bound for the risk level. Depending on how epistemic uncertainty is quantified, these bounds may correspond to the quantiles of a distribution or the extremes of an interval. Hence, in probabilistic approaches, comprehensiveness is achieved if the range of values delimited by these risk bounds is completely below or above the risk limit, because the repository can be conclusively deemed safe or unsafe, respectively (whereas the overlap of risk interval and risk limit would denote ambiguity).

With these premises, a probabilistic methodology is presented to quantify residual uncertainty and to evaluate comprehensiveness based on BNs. Specifically, the BN serves as system model in which nodes and directed arcs represent the FEPs and dependencies between them. The FEPs (chemical concentrations, water flows, etc.) take on discrete states such as low, medium and high, with different probabilities. For FEPs which depend on other ones (i.e., *children* and *parents*, see Section 2.2), these probabilities are conditional. The safety target, e.g., the dose rate to the public, is represented by a downstream node. This node has two states, which correspond to the respect and the violation of a given safety threshold, respectively.

A scenario is defined as a combination of states of the FEPs. Its probability is given by the joint probability of all its states, which can be calculated from unconditional and conditional FEP state probabilities (Section 2.1). Furthermore, for each scenario, there is a corresponding conditional probability of leading to the violation of the safety threshold. Subsequently, the total probability of the violation state at the safety target is the aggregation of these probabilities over all scenarios. This *violation probability* is taken as an estimate of the radiological risk brought by the nuclear waste management facility.

In an ideal setting, safety could be assessed by comparing the violation probability (i.e., risk level) with a maximum acceptable value (i.e., risk limit). However, in real problems, epistemic uncertainty implies that probabilities cannot be known precisely, and neither can risk. The uncertainty about the state probabilities of the FEPs and of the safety target can be characterized with different techniques depending on the source of information.

One source is represented by computer simulations which describe the dependence of a given FEP (or the safety target) on its parents. A simulation can thus be interpreted as a multinomial trial, where a given input (set of parents' states) can result in one out of various possible outcomes (states of the child). Here, the uncertainty is that the repeated simulation of the same input may give a different result. Accordingly, counters of simulation results can be used for estimating conditional probability intervals through the Imprecise Dirichlet Model (Walley, 1996).

Another source of probabilistic information is expert judgment (Coppersmith, et al., 2009; Dias, et al., 2018; Soares, et al., 2018). In this case, the uncertainty is that two or more experts may have different beliefs about the same vector of state probabilities at a given node. This diversity can be characterized by admitting all convex combinations of the experts' beliefs as feasible probability values.

All these epistemic uncertainties about the state probabilities are propagated through the BN to quantify the residual uncertainty about the violation probability. Such propagation can be framed as an optimization problem in which i) the objective function is the violation probability expressed as a function of the state probabilities in the BN, and ii) the feasible region is determined by the linear constraints imposed by the bounds to the conditional probabilities and the convex hulls of experts' beliefs. The lower and upper bounds for the violation probability are found by solving this optimization problem first as a minimization and then as a maximization. Because the violation probability is a multilinear function of the state probabilities, the optimization is performed by a routine of multilinear programming that combines the simplex and reduced-gradient methods for linear and nonlinear problems, respectively.

If the corresponding violation probability interval is entirely below the maximum acceptable value, then comprehensiveness is achieved because it is possible to infer that the facility is sufficiently safe. An interval completely above the limit would instead indicate that the facility poses an excessive risk to the public. Such an analysis would equally be comprehensive as the conclusion would simply be the opposite. If the violation probability interval overlaps the acceptable limit, no conclusion is warranted about the safety of the nuclear waste management facility.

Because a narrower risk interval is less likely to overlap the risk limit, reducing residual uncertainty helps pursue comprehensiveness. Operatively, this can be done by acquiring additional information. To this end, this paper presents the adaptive Bayesian sampling algorithm for prioritizing which combinations of FEP states should be chosen as simulation input for tightening the violation probability interval. Analogously, for probabilities elicited by expert judgment, a sensitivity analysis based on *contraction* (Larsson, et al., 2005) is employed to identify for which FEPs the attainment of a greater degree of consensus among the experts would lead to less residual uncertainty.

In collaboration with the Belgian centre of nuclear studies SCK·CEN, the proposed BN-based methodology is applied to the near-surface repository planned for the site of Dessel (Belgium). For benchmarking, the analysis is first performed following a pluralistic approach, i.e., by formulating 13 scenarios based on various assumptions about the loss of functionality of the containment barriers. Each scenario is simulated with COMSOL Multiphysics, and the resulting dose rate to the public is checked against a safety threshold (taken to be a fraction of the regulatory limit). While most scenarios comply with the threshold, few scenarios do lead to violations. With this pluralistic approach, though, the lack of a probabilistic characterization of the scenarios prevents any quantification of the overall risk level.

The analysis is repeated by adopting the probabilistic methodology presented in this paper. A BN is built to include the FEPs that can significantly affect the evolution of the repository barriers. The dependencies between these FEPs are also identified and indicated as directed arcs. The safety target is set to be the dose rate to the population, whose violation state corresponds to the exceedance of the previously mentioned safety threshold.

Illustrative probability values for the FEP states are derived from preliminary statistical analyses of the SCK·CEN, and mathematically treated as experts' beliefs. The results of COMSOL simulations are instead used for obtaining bounds to the probabilities of the violation state, conditioned on each combination of states of the safety target's parents.

Specifically, 1,000 simulations are run by randomly sampling the input FEP states. From the simulation results, the corresponding interval for the violation probability can be inferred to be [0.003, 0.990]. Successively, the analysis is carried out from the start, this time assigning the input of the 1,000 simulations through the adaptive Bayesian sampling algorithm. While the violation-probability interval [0.033, 0.856] is much narrower than in the initial set-up, the overwhelming residual uncertainty signals that comprehensiveness is not achieved.

It is estimated that about 50,000 additional simulations would be required to gather a stronger knowledge about the violation probability and attain comprehensiveness. Nevertheless, it has at least been demonstrated that only a probabilistic approach makes it possible to quantify residual uncertainty and assess whether additional information is needed.

3.4 Paper 3 bis

This data article reports and illustrates the input data for the case study of Paper 3. First, an overview is given of the conceptual model of the nuclear waste repository implemented in the COMSOL Multiphysics simulation software, and of its physical and chemical parameters. The values of these parameters for the thirteen scenarios analyzed with a pluralistic approach are also listed. Then, the development of the BN for modeling the repository with the methodology of Paper 3 is illustrated.

The most significant parameters of COMSOL Multiphysics are taken as FEPs (i.e., the nodes of the network). This requires that their ranges of values be discretized into adjacent intervals for the definition of the FEP states (e.g., low, medium and high). An exception is the FEP "Earthquake" which does not have a corresponding variable in COMSOL Multiphysics, but is characterized by the discrete states "Beyond design-basis" and "Major".

The FEP state probabilities are also given. For each FEP, two to three assumptions are made about the values of the (conditional or unconditional) vector of state probabilities. These assumptions correspond to illustrative probability distributions (e.g., log-uniform, log-triangular) and, in a realistic safety assessment, may represent the beliefs of different experts.

Finally, the priors for the probability of violating the safety threshold conditioned on each of the 576 subscenarios [1] of the safety target (i.e., the dose rate to the public) are listed. These priors serve as an input to the adaptive Bayesian sampling algorithm in Paper 3, and employed as the frequencies with which violation has been observed in previous runs of the subscenarios in COMSOL Multiphysics.

3.5 Paper 4

In the previous paper the system is modeled as a BN, in which the direction of systemic dependencies is predetermined. In reality, the system structure is not always as easy to specify. This paper considers systems in which the dependencies between the factors (i.e., the FEPs) are not necessarily known.

To characterize dependencies, this paper presents *probabilistic cross-impact ratios*. For any pair of FEPs and states thereof, this ratio is defined as the joint probability of these states divided by the product of the states' marginal probabilities.

A cross-impact ratio of 1 denotes independence, because the product of marginal probabilities represents the joint probability of the states if the FEPs are stochastically independent. Conversely, a larger value is a sign of synergetic effects so that the two states are more likely to occur together. When the ratio is lower than 1, instead, there are antagonistic effects such that the occurrence of one state diminishes the probability of the other. The definition of cross-impact ratios is symmetric in that it does not distinguish which FEP influences the other.

Probabilistic ratios strengthen the methodological foundations to cross-impact analysis by enriching the description of the influences between system factors with a probabilistic interpretation. In fact, traditional cross-impact analysis relies on assigning a semi-quantitative score (known as cross-impact term) to the likelihood of a given pair of system factor states. For instance, cross-impact terms are utilized for screening out scenarios which contain states that are deemed too unlikely to occur together. Arguably, this criterion is overly strict in that it may

---

[1] In Paper 3, a subscenario at a given node is defined as a combination of states of the node's parents.

lead to the outright exclusion of scenarios which, although improbable, can still have a nonnegligible contribution to the overall risk (Section 2.4).

The cross-impact ratios can be written as a function of the scenario probabilities, thus creating a link between systemic dependencies and risk. On a side note, the notion of violation probability of Paper 3 is here extended to that of expected disutility, i.e., the mean value of the disutility (measured on a 0-100% scale) of the scenario impacts.

Epistemic uncertainties about the cross-impact ratios can be quantified by placing bounds. Along with those for the marginal probabilities of the FEP states, such bounds can be encoded in an optimization problem in which the risk expression becomes the objective function to be minimized and maximized to find the lower and upper risk bounds, respectively. This notwithstanding, these optimization problems can be even harder than in Paper 3 because the bounds to the ratios, when expressed in terms of the scenario probabilities, involve nonlinear constraints (wherefore the task can be carried out by state-of-the-art approaches).

The proposed approach is applied to the same repository as in Paper 3 to measure risk as the probability that the dose rate to the public violates a given safety threshold. The interpretation from the viewpoint of expected disutility is that dose rates below and above the safety threshold have 0 and 100% disutility, respectively.

The case study is nonetheless revisited, in that the FEPs which compose the system are no longer organized in a structured network. Also, while Paper 3 focuses on the decision-making implications of the residual uncertainty about risk, this paper investigates the sensitivity of the risk estimate to varying information about systemic dependencies. Towards this goal, the BN of Paper 3 is employed as a source of probabilistic data. Three alternative settings are analyzed, each one comprising increasingly detailed information. These settings are compared with respect to the risk upper bound.

The first setting includes bounds about the marginal probabilities of the FEP states only. These are calculated by i) repeatedly sampling realizations of the joint probability distribution underlying the BN and, hence, of the scenario probabilities, ii) computing the corresponding values of the marginal probabilities and iii) taking the bounds in correspondence of predefined sample quantiles. No constraint is set to the cross-impact ratios. The FEPs are thus allowed to have any synergetic dependence that may increase the chances of unacceptable radiological impacts. As a result, the upper risk bound is 0.576.

The second setting also includes the dependencies between a selected set of FEPs (namely, the dependent FEPs connected by directed arcs in the BN). Bounds for cross-impact ratios associated with pairs of these FEPs' states are calculated with the same procedure based on sample quantiles as above. Once these constraints are implemented in the problem, the upper bound of the risk level becomes 0.571.

The third and last setting reproduces the dependence structure of the BN, by also enforcing the independence about the remaining FEPs (namely, the FEPs with no arc pointing towards them in the BN). Although this would imply the cross-impact ratios between the states of these and all other FEPs to be exactly 1, such constraints are relaxed by admitting narrow bounds around the unit value. The dependencies that can be established in the system are more limited than in the two previous setting, so that the risk upper bound drops to 0.427.

In summary, the biggest decrease in the risk level is here observed when the assumption of independence is introduced. This result emphasizes that independence should only be modeled when there is solid evidence and/or knowledge of the system under assessment.

3.6 Paper 5

Probabilistic approaches may be lacking in transparency if the focus is exclusively on the overall risk level. It is also important to understand which specific scenarios contribute most to risk, so that risk-management actions can be taken to avoid them. Even if the baseline risk is acceptable, identifying the riskiest scenarios supports transparency.

Risk importance measures (RIMs) are useful in this regard as they help identify those system components whose failure can compromise the safety performance of the overall system most. Nevertheless, while they are suitable for devices such as valves, pumps and generators, traditional RIMs do not apply to complex systems whose components' states cannot be *ex ante* mapped to the classifiers "functioning" or "failed". In nuclear waste management, for instance, the probability with which a given FEP state leads to the violation of the safety target may largely depend on the states of other FEPs.

To overcome this limitation, this paper presents RIMs for *scenarios*. Specifically, several traditional RIMs are redefined so that their argument is not a system component but a scenario (i.e., a combination of FEP states). Hence, these novel measures enable the analysis of systems in which i) the FEPs have multiple states (i.e., they are not binary), ii) the system structure and underlying probability distribution is modeled by a BN and iii) risk is estimated as an expected disutility (thus, not necessarily in binary terms of safety versus failure either). In this framework, the epistemic uncertainty about the probabilities in the network is not taken into account.

In particular, the following RIMs for scenarios are defined. The *risk achievement worth* (RAW) quantifies the relative risk change once the scenario is assumed to occur; the *risk reduction worth* (RRW) quantifies the relative risk change once the scenario is assumed *not* to occur; the *Birnbaum importance* (BI) quantifies the risk change in response to an incremental increase in a scenario probability (it also represents the difference between the updated risk levels once the scenario is assumed to occur and not to occur, respectively); the *criticality index* (CI) equals the BI multiplied by the scenario probability, but it also constitutes a rearrangement of the RRW (i.e., the inverse of 1 minus the RRW); lastly, the *risk share* (RS) quantifies the percentage of overall risk contributed by the scenario.

Although these measures are different functions of the scenario probabilities and impacts, they are mutually consistent in that they all identify the same set of *risky* scenarios. Each RIM has a limit value dividing the risky scenarios from the safer ones (e.g., RAW larger than 1, and RS larger than the scenario probability). The paper shows that, if a scenario exceeds this limit value for a measure, then it does for the remaining ones as well.

While identifying the same set of risky scenarios, the different measures may lead to different rankings of these risky scenarios. For any chosen measure, the *riskiest* scenario is defined as the one with the largest value. Nonetheless, even for a system of moderate size, the number of scenarios can be so large that the search of the riskiest one by explicit enumeration may be computationally infeasible. For an efficient search, optimization problems are formulated such that i) the objective function (to be maximized) is an expression of the chosen RIM as a function of binary variables through which scenarios can be formed by inclusion (value of 1) and exclusion (0) of the various FEP states, and ii) constraints can be placed to bound the search to specific scenarios (focusing, e.g., on a restricted set of FEPs, or on *causal scenarios* which indicate how specific states of a FEP are followed by specific states of its dependent FEPs).

These are mixed-integer linear programming problems, which can be solved through tailored algorithms. Scenario rankings are obtained by carrying out the optimization repeatedly, each time adding a constraint that prevents the previously found scenario to be picked as the one which maximizes the chosen RIM.

The novel RIMs for scenarios are first tested on a literature case study where the system components' states can in fact be characterized as functioning or failed. The results are consistent with the original study, thus demonstrating the generality of the new measures.

The second case study represents the mechanisms which can cause human errors in the storage of spent nuclear fuel at the site of Sizewell (United Kingdom). This is a more complex system, not amenable to be studied with traditional RIMs. In turn, in keeping with earlier literature findings (Groth & Mosleh, 2011; Groth & Mosleh, 2012), the novel RIMs shed light on the scenario in which knowledgeable operators may have an increased risk of errors due to an overconfident attitude.

Building on the results from the case studies, some guidelines are given on using the RIMs for scenarios in risk management. For instance, the overall risk can be reduced by implementing actions to exclude scenarios with either or both high RRW and RS. To choose which specific FEP states to prevent when trying to exclude a scenario, RIMs may be used in combination. For example, risk managers should make sure to prevent FEP states which, when analyzed as scenarios in their own right, have a RAW larger than 1. Apart from this combined use, excluding scenarios with high RAW serves for risk avoidance more than risk reduction. In this case, the purpose would be to eliminate scenarios which would have an enormous impact if they were to occur, even if they do not contribute much to risk due to their very low probability. Finally, in order to exclude a scenario, it is possible to act on dependencies rather than preventing FEP states altogether. In practice, especially if this implies a reduced use of resources, one could focus on zeroing the probability of the risky FEP state only in cascade of another specific FEP state.

4. Concluding perspectives

Based on the insights from the papers of Section 3, suggestions are given on how to achieve comprehensiveness in scenario analysis for risk assessment. In particular, it is important to i) model systemic dependencies, ii) characterize uncertainty and iii) ensure transparency. These suggestions are discussed in sections 4.2 through 4.1. Finally, Section 4.4 highlights some research topics to be further developed. While the main viewpoint is that of nuclear waste management, recommendations are intended to be valid for other fields as well.

4.1 Modeling systemic dependencies

System models represent the nuclear waste management facility as a set of FEPs and dependencies thereof (see Paper 1). The graphical representation (e.g., a network) is parameterized through a mathematical quantification of these systemic dependencies.

In BNs, conditional probabilities indicate changes in the likelihood of a given FEP state due to changes in the state of other FEPs (see Paper 3). The novel risk importance measures for scenarios (see Paper 5) help detect increased risk levels if a given FEP state occurs in combination or sequence with a specific state of another FEP. Alternatively, probabilistic cross-impact ratios (see Paper 4) can be elicited to capture synergetic (or antagonistic) dependencies between FEPs such that specific pairs of their states are more (or less) likely to occur together.

If the system factors are assumed to be independent even if they are not, risk can be underestimated. In the example of Paper 4 where independence is enforced between some FEPs, the radiological risk is almost 34% lower than when there are dependencies between these FEPs.

Another example is the simple BN of Figure 3, in which nodes A, B and C have binary states 0 and 1. Risk can be assessed as the overall probability of the unacceptable state “Vio” at node D. At node A (Figure 3, left), assume that the probability mass of both states 0 and 1 is 0.5. Further assume that the states of B and C are the same as that of A. Finally, assume the conditional probability of state “Vio” at node D is 1 if B and C are both in state 1, and 0 otherwise. This network structure implies the overall probability of state “Vio” to be the probability of state 1 at node A, which is therefore 50%. Suppose now that the dependence between nodes B and C through A is neglected (Figure 3, right), and that the probabilities of their states 0 and 1 are taken to have their marginal values in the previous network, i.e., 50% each. Then, the overall violation probability at node D becomes that of B and C both being in state 1, thus dropping down to 25%.

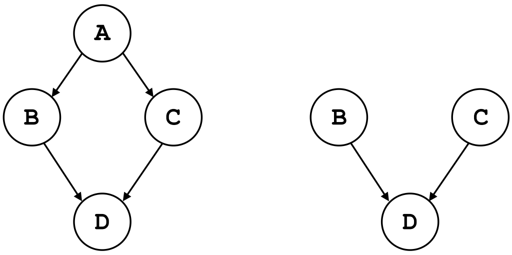

Figure 3. Bayesian network with (left) and without (right) considering possible systemic dependencies.

4.2 Characterizing uncertainty

Quantifying uncertainty is important for risk-informed decision making. Helton et al. (2000) note that the "*disclosure of uncertainty enables the scientific reviewer, as well as the decision maker, to evaluate the degree of confidence that one should have in the risk assessment*". Also, uncertainty "*may not be critical if the confidence intervals about the risk estimate (...) are clearly below regulatory levels of concern*" (Helton, et al., 2000). In turn, if the risk "*intervals overlap the regulatory levels of concern, consideration should be given to reduce the uncertainty in the risk estimate*" (Helton, et al., 2000). This idea has lost momentum in nuclear waste management, where, especially in Europe, the pluralistic approach has continued to prevail (see Paper 1).

Uncertainty can be best quantified with probabilistic approaches. Probabilities are suitable for characterizing aleatory uncertainty about which states of the FEPs (i.e., the relevant factors for describing the evolution of the nuclear waste management facility) and scenarios are more likely. Epistemic uncertainties, too, can be characterized by probability distributions.

With this in mind, one issue is how to characterize the uncertainty related to a given variable, such as the water flow, or the distribution coefficient which quantifies the tendency of water contaminants to adsorb onto the particles of the porous material they flow through. In Paper 3 both are modeled as FEPs, meaning that the probability distributions over their states are a characterization of aleatory uncertainty. In Paper 2, though, the same variables are simulation-model parameters, whose distributions are instead an expression of epistemic uncertainty. What is the rationale of this apparent contradiction?

Sumerling et al. (1993) suggest that variables without considerable uncertainty need not be modeled as FEPs. More generally, if the risk assessor intends to use a variable in scenario generation (as in Paper 3), then this variable should be treated as a FEP. Modeling variables that can be targeted in risk management as FEPs helps identify which of their states appear in the riskiest scenarios and should therefore be prevented. Conversely, variables that are deemed of no relevance for scenario generation can be modeled as "mere" parameters. If there is no interest to define scenarios in the first place, for example when the analysis regards a single chain of known events as in Paper 2, no variable needs to be a FEP.

The flexibility of modeling the uncertainty about a variable as aleatory or epistemic is consistent with the model-oriented categorization of uncertainty discussed in Section 1.2. Once uncertainties have been characterized, and distinguished between aleatory and epistemic accordingly, risk assessors can show the effects of these uncertainties (separately) in the results of the risk assessment.

In this respect, Paper 2 highlights that, even in the absence of aleatory uncertainty, the epistemic uncertainty does not allow for the deterministic prediction of the radiological impact. The latter should then be quantified through a risk estimate, e.g., an expected value or a violation probability. When there are both types of uncertainty, their effect can be shown separately by also quantifying the imprecision in the risk estimate itself.

For example, in the risk assessment of the Yucca Mountain repository, probability distributions are defined to characterize the aleatory uncertainty about the arrival of disruptive events (volcanic eruptions, earthquakes, etc.), so that risk is estimated as the expected value of the dose rate to the public. In turn, epistemic uncertainty is characterized by defining probability distributions for the parameters (e.g., means and variances) of these probability distributions. The implication is that the expected value of the radiological impact becomes a random variable itself. Then, uncertainty is propagated through double-loop Monte Carlo sampling (Helton & Sallaberry, 2009) to estimate the *expected value of the expected value* of the dose rate to the public.

In Paper 3 the uncertainty about the risk estimate is named *residual*, because it is what remains after the epistemic uncertainties in the model are quantified and propagated to the risk estimate. Building on Helton et al. (2000), it is therefore suggested that comprehensiveness in scenario analysis is achieved if residual uncertainty is sufficiently small to assess conclusively whether the risk level is acceptable or not. This is intended as a generalized interpretation of comprehensiveness, in contrast to the subjective interpretations found in current approaches to scenario analysis.

Paper 3 considers nonprobabilistic characterizations of uncertainty. Specifically, it proposes a hybrid model in which aleatory uncertainty and risk are quantified through probabilities, but the epistemic uncertainty about these probabilities is characterized by imprecise values (i.e., bounds). In general, probabilities may be argued to be the most suitable variables for characterizing aleatory uncertainty. Then, risk assessors may evaluate in each specific risk assessment which technique best suits the characterization of the epistemic uncertainty about these variables.

Pluralistic approaches are less suitable than probabilistic ones to characterize uncertainty, quantify residual uncertainty and evaluate comprehensiveness. Still, in applications where the attention is mostly placed on scenario impacts, they can provide valuable insights about the system response through various *what-if* scenarios. To take an example outside nuclear waste management, the results of financial institutions can be stress-tested under the assumption of severe economical shocks. Here, rather than by the FEPs, the system factors are represented by macroeconomic variables such as GDP growth, unemployment rate and inflation.

Yet, without scenario probabilities, it is not possible to define a quantitative estimate of the overall risk in the system, let alone quantify the residual uncertainty. A risk estimate is instead essential when there are higher stakes, such as the safety of the public exposed to the radioactive releases of a nuclear waste management facility.

4.3 Ensuring transparency

There is much discussion on whether showing uncertainty can decrease (Siegrist, 2019) or not (Van der Bles, et al., 2020) the lay stakeholder’s trust in a risk assessment. In any case, it can be argued that communicating uncertainty is an act of transparency.

From this viewpoint, the pluralistic approach has the merit of distinctly displaying the radiological impact of each scenario. Probabilistic approaches, instead, may be perceived as black boxes that produce an overall risk estimate without clarifying the contribution of different scenarios.

Hence, along with the overall risk level, it is advisable to calculate risk importance measures for scenarios (see Paper 5). A set of such measures exists, each one being a specific function of the probability and impact of a given scenario. Thus, scenarios can be ranked and targeted in risk management based on how risky they are.

Probabilistic approaches are also criticized on the grounds that any risk estimate would be essentially meaningless (Chapman, et al., 1995). The uncertainty about the impact of FEPs that have been overlooked in the risk assessment would be incomparably larger than the aleatory and epistemic uncertainties quantified in the risk estimate. It is useful to revisit this claim by drawing a line between comprehensiveness in FEP identification and comprehensiveness in scenario generation.

In scenario generation, the risk in the system is assessed based on the probabilities and impacts of the scenarios. As previously discussed, comprehensiveness can be evaluated by quantifying the uncertainty about these quantities (probabilities, impacts and risk). This presumes that the system is exhaustively represented by the set of FEPs which have been identified. This is why at the earlier stage of FEP identification comprehensiveness requires that all the FEPs which can *significantly* affect the repository be included in the risk assessment (see Paper 1).

Because comprehensiveness at the FEP level cannot be evaluated quantitatively, risk assessors are advised to guarantee transparency. Transparency can be attained by building a system model in which the nuclear waste management facility is represented as a set of FEPs. Especially when in a graphical form, a system model gives a clear view on which FEPs have been included in the risk assessment. The separation between comprehensiveness in FEP identification and scenario generation allows risk assessors to first do their best to identify the most significant FEPs, and then to estimate risk and evaluate comprehensiveness within the system represented by these FEPs.

4.4 Further research avenues

There are several further research topics. The first one is represented by the black-striped area of Figure 2, in which the three boxes with the suggestions for scenario analysis overlap. This would require a unified methodology that embraces the three recommendations above at the same time. Such a methodology could be still based on a BN, but where risk importance measures (RIMs) for scenarios are calculated taking imprecise probabilities into account. Here, a double challenge would arise from the optimization models by which the RIMs are computed. One is that the problems would become mixed-integer *nonlinear* programmes and, as such, much harder to solve. The other is that the RIMs would also be interval-valued, wherefore the ranking of the risky scenarios may not be unique. A solution may be to import the concept of dominance from the realm of decision making and identify the set of *non-risk-dominated* scenarios. Specifically, these scenarios would be deemed riskier than the others in spite of the imprecision in the RIMs.

Second, the BNs in this dissertation are static, as they imply a unique causal flow from the independent FEPs to the dependent ones and, hence, to the safety target. This does not explicitly capture feedback loops between the FEPs even if these appear in the evolution of nuclear waste repositories. To account for these cyclic dependencies and to evaluate their effect over the lifetime of the system, *dynamic* BNs (Poropudas & Virtanen, 2011; Mancuso, et al., 2019) can be developed.

Third, BNs need not be employed as a system model. For instance, with no prior knowledge of the systemic dependencies, a very large number of computer-simulation runs may be produced to span as many possible scenarios depicting alternative ways in which the nuclear waste management facility could evolve. Then, one may post-processing these scenarios to examine which patterns of combinations and sequences of FEPs realizations have most impact (Antonello, et al., 2020). This post-processing may build on data-mining techniques, possibly drawing from the recent family of approaches for *integrated deterministic and probabilistic safety assessment* (Zio, 2014). The use of these techniques requires i) simulation models of the dependencies between all relevant FEPs (limiting any need for expert judgments to the probability distributions of the simulation input, i.e., the values of the independent FEPs), and ii) sufficient computational power to run a vast number of simulations in a useful time.

Fourth, the probability distributions of the input variables (namely, FEPs and other physical-chemical parameters) employed in computer simulations could be defined based on *extreme-value theory* (Cirillo & Taleb, 2016; Cirillo & Taleb, 2020). For instance, in fat-tail distributions, the probability mass decays so slowly towards the distribution tail(s) that extreme values are not negligible in risk assessments.

Assume that, as an effect of fat-tailed input variables, the dose rate to the public also has a fat-tail distribution, say, a power law. Then, it can be the case that the sample mean after 999 simulations is 0.24 mSv/y, and the (estimated) probability of violating the regulatory threshold of 1 mSv/y is 0.029 [2]. Further, assume that the dose rate in the 1000th simulation is 8,937 mSv/y (an amount which, absorbed in a short time lapse, compares to those experienced by workers in the Chernobyl accident; oecd-nea.org/chernobyl). Here, the combined use of sample mean and violation probability fails to give a well-rounded characterization of risk. In fact, the violation probability only rises to 0.030, whereas the sample mean rises to 9.18 mSv/y. This is because fat-tailed random variables may not even have well-defined expected values (like in this example, where all moments are infinite), causing the sample mean to converge too slowly, or not to converge at all, to be a stable indicator.

Extreme-value theory implies that the focus of risk assessment is shifted from expected values to maxima. This may lead to more demanding requirements for the design of the nuclear waste management facility (Montonen, et al., 2020). If there is no evidence that the input variables of the risk assessment should be modeled as fat-tailed (for example if normal distributions show a better fit with observed frequencies), these requirements may create tensions between the safety authority and the agency in charge of constructing the facility.

A compromise may be to i) perform a risk assessment with distributions consistent with historical data and/or expert judgments (hence, not necessarily fat-tailed) to inform the licensing decision, and then ii) repeat the assessment by using a probabilistic what-if analysis in which fat-tailed distributions are assumed regardless of the evidence. Rather than for approving the barrier design, the results of the second assessment may be used to elaborate mitigation strategies against catastrophic outcomes (e.g., by writing an evacuation plan for the

---

[2] These figures are produced by sampling from a power-law distribution with slope coefficient $\alpha = 2$ and minimum value 0.05 mSv/y.

population in case of large radioactive releases instead of increasing the thickness of the waste containers by ten times).

References

Antonello, F. et al., 2020. Association rules extraction for the identification of functional dependencies in complex technical infrastructures. *Reliability Engineering and System Safety, In press.*

Asan, S. S. & Asan, U., 2007. Qualitative cross-impact analysis with time consideration. *Technological Forecasting & Social Change,* Volume 74, pp. 627-644.

Aven, T. & Zio, E., 2011. Some considerations on the treatment of uncertainties in risk assessment for practical decision making. *Reliability Engineering and System Safety,* Volume 96, pp. 64-74.

Balch, M. S., 2012. Mathematical foundations for a theory of confidence structures. *International Journal of Approximate Reasoning,* Volume 53, pp. 1003-1019.

Barlow, R. E. & Proschan, F., 1975. Importance of system components and fault tree events. *Stochastic Processes with Their Applications,* Volume 3, pp. 153-173.

Bear, J., 1979. *Hydraulics of groundwater.* New York: McGraw-Hill.

Bear, J. & Cheng, A., 2010. *Modeling groundwater flow and contaminant transport.* Dordrecht: Springer.

Beer, M., Ferson, S. & Kreinovich, V., 2013. Imprecise probabilities in engineering analyses. *Mechanical Systems and Signal Processing,* Volume 37, pp. 4-29.

Beeson, S. & Andrews, J. D., 2003. Importance measures for non-coherent-system analysis. *IEEE Trasactions on Reliability,* 52(3), pp. 301-310.

Birnbaum, Z. W., 1969. On the importance of different elements in a multielement system. In: P. R. Krishnaiah, ed. *Multivariate Analysis II.* New York: NY: Academic Press, pp. 1-15.

Borgonovo, E., 2010. The reliability importance of components and prime implicants in coherent and non-coherent systems including total-order interactions. *European Journal of Operational Research,* Volume 204, pp. 485-495.

Borgonovo, E. & Apostolakis, G. E., 2001. A new importance measure for risk-informed decision making. *Reliability Engineering and System Safety,* Volume 72, pp. 193-212.

Borgonovo, E. & Cillo, A., 2017. Deciding with thresholds: importance measures and value of information. *Risk Analysis,* 37(10), pp. 1828-1848.

Cadini, F., Bertoli, I., De Sanctis, J. & Zio, E., 2012. A novel particle tracking scheme for modeling contaminant transport in a dual-continua fractured medium. *Water Resources Research,* 48(W10517), pp. 1-11.

Cadini, F., Bertoli, I., De Sanctis, J. & Zio, E., 2013. Monte Carlo simulation of radionuclide migration in fractured rock for the performance assessment of radioactive waste repositories. *Reliability Engineering and System Safety,* Volume 111, pp. 241-247.

Cadini, F. et al., 2010 (a). Monte Carlo estimation of radionuclide release at a repository scale. *Annals of Nuclear Energy,* Volume 37, pp. 861-866.

Cadini, F. et al., 2010 (b). Monte Carlo-based assessment of the safety performance of a radioctive waste repository. *Reliability Engineering and System Safety,* Volume 95, pp. 859-865.

Chapman, N. A. et al., 1995. *Systems analysis, scenario construction and consequence analysis definition for SITE 94,* Stockholm: SKI.

Chapman, N. A. & McKinley, I. G., 1987. *The geological disposal of nuclear waste.* Chichester, UK: Wiley.

Cirillo, P. & Taleb, N. N., 2016. On the statistical properties and tail risk of violent conflicts. *Physica A,* Volume 452, pp. 29-45.

Cirillo, P. & Taleb, N. N., 2020. Tail risk of contagious diseases. *Nature Physics,* Volume 16, pp. 606-613.

Coppersmith, K., Jenni, K. E., Perman, R. & Youngs, R., 2009. Formal expert assessment in probabilistic seismic and volcanic hazard analysis. In: C. Connor, N. A. Chapman & L. Connor, eds. *Volcanic and Tectonic Hazard Assessment for Nuclear Facilities.* Cambridge: Cambridge University Press, pp. 593-611.

Der Kiureghian, A. & Ditlevsen, O., 2009. Aleatory or Epistemic? Does it matter?. *Structural Safety,* 31(2), pp. 105-112.

Di Maio, F., Baronchelli, S. & Zio, E., 2015. A computational framework for prime implicants identification in noncoherent dynamic systems. *Risk Analysis,* 35(1), pp. 142-156.

Dias, L. C., Morton, A. & Quigley, J., 2018. *Elicitation - The science and art of structuring judgment.* London: Springer.

Echard, B., Gayton, N. & Lemaire, M., 2011. AK-MCS: an active learning reliability method combining Kriging and Monte Carlo simulaton. *Structural Safety,* Volume 33, pp. 145-154.

Ferson, S., Balch, M., Sentz, K. & Siegrist, J., 2013. *Computing with confidence.* Compiègne, 8th International Symposium on Imprecise Probabiltiy: Theories and Applications.

Fox, C. R. & Ülkümen, G., 2011. Distinguishing two dimensions of uncertainty. In: *Perspectives on thinking, judging, and decision making.* Oslo: Universitetsforlaget, pp. 21-35.

Fussell, J. B., 1975. How to hand-calculate system reliability and safety characteristics. *IEEE Transaction on Reliability,* R-24(3), pp. 169-174.

Galson, D. A. et al., 2000. Scenario development for the Waste Isolation Pilot Plant compliance certification application. *Reliability Engineering and System Safety,* Volume 69, pp. 129-149.

Giacobbo, F. & Patelli, E., 2008. Monte Carlo simulation of nonlinear reactive contaminant transport in unsaturated porous media. *Annals of Nuclear Energy,* Volume 34, pp. 51-63.

Goldberg, D., 1989. *Genetic algorithm in search, optimization, and machine learning*. Boston: Addison-Wesley Publishing Company.

Goodwin, B. W. et al., 1994. *The disposal of Canada's nuclear fuel waste: post closure assessment of a reference system,* Pinawa: AECL.

Groth, K. M. & Mosleh, A., 2011. *Development and use of a Bayesian network to estimate human error probability*. Wilmington, NC, ANS PSA 2011 International Topical Meeting on Probabilistic Safety Assessment and Analysis.

Groth, K. M. & Mosleh, A., 2012. Deriving causal Bayesian networks from human reliability analysis data: a methodology and example model. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability,* 226(4), pp. 361-379.

Helton, J. C. et al., 2000. Conceptual structure of the 1996 performance assessment for the Waste Isolation Pilot Plant. *Reliability Engineering and System Safety,* Volume 69, pp. 151-165.

Helton, J. C. & Sallaberry, C. J., 2009. Computational implementation of sampling-based approaches to the calculation of expected dose in performance assessments for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. *Reliability Engineering and System Safety,* Volume 94, pp. 699-721.

Hora, S. C., 1996. Aleatory and epistemic uncertainty in probabilisty elicitation with an example from hazardous waste management. *Reliability Engineering and System Safety,* Volume 54, pp. 217-223.

Hutri, K. L. & Antikainen, J., 2002. Modelling of the bedrock response to glacial loading at the Olkiluoto site, Finland. *Engineering Geology,* Volume 67, pp. 39-49.

ICRP, 2012. *Compendium on dose coefficients based on ICRP publication 60,* Amsterdam: Elsevier Ltd.

Jensen, V., 2001. *Bayesian networks and decision graphs*. New York: Springer-Verlaag.

Käki, A., Salo, A. & Talluri, S., 2015. Disruptions in supply networks: a probabilistic risk assessment approach. *Journal of Business Logistics,* 36(3), pp. 273-287.

Khayyun, T. S., 2018. Simulation of groundwater flow and migration of the radioactive Cobalt-60 from LAMA Nuclear Facility-Iraq. *Water,* 10(176), pp. 1-14.

Larsson, A., Johansson, J., Ekenberg, L. & Danielson, M., 2005. Decision analysis with multiple objectives in a framework for evaluating imprecision. *International Journal of Uncertainty, Fuzziness and Knowledge-based Systems,* 13(5), pp. 495-510.

Lee, Y. M. & Hwang, Y., 2009. A GoldSim model for the safety assessment of an HLW repository. *Progress in Nuclear Energy,* 51(6-7), pp. 746-759.

Leinonen, A., Rasilainen, K., Komonen, P. & Gotcheva, N., 2021. *Nuclear waste repository as a scenario problem: developing epistemic understanding,* Espoo: VTT Technical Research Centre of Finland.

Levitin, G., Podofillini, L. & Zio, E., 2003. Generalised importance measures for multi-state elements based on performance level restrictions. *Reliability Engineering and System Safety,* Volume 82, pp. 287-298.

Mallants, D. & Chapman, N. A., 2020. How much does corrosion of nuclear waste matrices matter. *Nature Materials,* Volume 19, pp. 959-961.

Mancuso, A., Compare, M., Salo, A. & Zio, E., 2017. Portfolio optimization of safety measures for reducing risks in nuclear systems. *Reliability Engineering and System Safety,* Volume 167, p. 20.29.

Mancuso, A., Compare, M., Salo, A. & Zio, E., 2017. *Risk-informed decision making under imprecise information: portfolio decision analysis and credal networks.* Portroz, 27th European Safety and Reliability Conference.

Mancuso, A., Compare, M., Salo, A. & Zio, E., 2019. Portfolio optimization of safety measures for the prevention of time-dependent accident scenarios. *Reliability Engineering and System Safety,* Volume 190, pp. 1-9.

Marseguerra, M. & Zio, E., 1997. Modelling the transport of contaminants in groundwater as a branching stochastic process. *Annals of Nuclear Energy,* Volume 24, pp. 325-644.

Montonen, O. et al., 2020. Multiobjective mixed integer nonlinear model to plan the schedule for the final disposal of the spent nuclear fuel in Finland. *Mathematics,* 8(528), pp. 1-29.

Natvig, B., 1979. A suggestion of a new measure of importance of system components. *Stochastic Processes and Their Applications,* Volume 9, pp. 319-330.

Noroozian, A., Kazemzadeh, R. B., Niaki, S. T. A. & E, Z., 2018. System risk importance analysis using Bayesian Networks. *International Journal of Reliability, Quality and Safety Engineering,* 25(1), pp. 1-26.

Pearl, J., 1987. Evidential reasoning using stochastic simulation of causal models. *Artificial Intelligence,* Volume 32, pp. 245-257.

Pearl, J. & Russell, S., 2003. Bayesian networks. In: M. A. Arbib, ed. *Handbook of brain theory and neural networks.* Cambridge: MIT Press, pp. 157-160.

Pearl, J. & Verma, T., 1992. A statistical semantics for causation. *Statistics and Computing,* Volume 2, pp. 91-95.

Poropudas, J. & Virtanen, K., 2011. Simulation metamodeling with dynamic Bayesian networks. *European Journal of Operational Research,* 214(3), pp. 644-655.

Posiva Oy, 2012. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto - Formulation of Radionuclide Release Scenarios 2012,* Eurajoki: Posiva Oy.

Rechard, R. P., Freeze, G. A. & Perry, F. V., 2014. Hazards and scenarios examined for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. *Reliability Engineering and System Safety,* Volume 122, pp. 74-95.

Rochelle, C. A. et al., 1994. *Migration of cement pore fluids from a radioactive waste repository: experimental studies of chlorite dissolution rates.* Edinburgh, Goldmisth Conference, pp. 779-780.

Savage, D., Cave, M. R., Milodowski, A. E. & George, I., 1987. Hydrothermal alteration of granite by meteoric fluid: an example from the Carnmenellis Granite, United Kingdom. *Contributions to Mineralogy and Petrology,* Volume 96, pp. 391-405.

Seetharam, A., Perko, J., Maliants, D. & Jacques, D., 2012. *Model assumptions for the cementitious near field of the Dessel near surface repository,* Brussels: ONDRAF/NIRAS.

Siegrist, M., 2019. *Uncertainties about the communication of uncertainties.* Berlin, Germany, International Conference on Uncertainty in Risk Analysis.

Soares, M. O., Sharples, L. M. A., Claxton, K. & Boyle, L., 2018. Experiences of structured elicitation for model-based cost-effectiveness analyses. *Value in Health,* Volume 21, pp. 715-723.

Society for Risk Analysis, 2018. *Society for Risk Analysis glossary,* McLean: Society for Risk Analysis.

Sumerling, T. J. & Thompson, B. G. J., 1992. *Application of a probabilistic system-model based methodology for the performance assessment of deep underground disposal of nuclear wastes.* Las Vegas, NV, 3rd International Conference on High-level Radioactive Waste Management.

Sumerling, T. J., Zuidema, P., Grogan, H. A. & vsn Dorp, F., 1993. *Scenario development for safety demonstration for deep geological disposal in Switzerland.* Las Vegas, NV, 4th International Conference on High-level Radioactive Waste Management.

Tolo, S., Patelli, E. & Beer, M., 2016. Risk assessment of spent nuclear fuel facilities considering climate change. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering,* 3(2).

Tolo, S., Patelli, E. & Beer, M., 2017 (a). Sensitivity analysis for Bayesian networks with interval probabilities. In: Walls, Revie & Bedford, eds. *Risk, Reliability and Safety: Innovating Theory and Practice.* London: Taylor & Francis Group, pp. 306-312.

Tolo, S., Patelli, E. & Beer, M., 2017 (b). Robust vulnerability analysis of nuclear facilities subject to external hazards. *Stochastic Environmental Research and Risk Assessment,* Volume 31, pp. 2733-2756.

Toppila, A. & Salo, A., 2013. A computational framework for prioritization of events in fault tree analysis under interval-valued probabilities. *IEEE Transaction on Reliability,* 62(3), pp. 583-595.

Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modeling. *Echological Modeling,* Volume 203, pp. 312-318.

Van der Bles, A. M., Van der Linden, S., Freeman, A. L. J. & Spiegelhalter, D. J., 2020. *The effects of communicating uncertainty on public trust in facts and numbers.* PsyArXiv, Proceedings of the National Academy of Sciences.

Walley, P., 1991. *Statistical reasoning with imprecise probabilities.* London: Chapman & Hall.

Walley, P., 1996. Inferences from multinomial data: learning about a bag of marbles. *Journal of the Royal Statistical Society, Series B (methodological),* 58(1), pp. 3-57.

Weimer-Jehle, W., 2006. Cross-impact balances: a system-theoretical approach to cross-impact analysis. *Technological Forecasting & Social Change,* Volume 73, pp. 334-361.

Weimer-Jehle, W., 2008. Cross-impact balances applying pair interaction systems and multi-value Kauffman nets to multidisciplinary systems analysis. *Physica A,* Volume 387, pp. 3689-3700.

Wei, P., Liu, F., Valdebenito, M. & Beer, M., 2021. Bayesian probabilistic propagation of imprecise probabilities with large epistemic uncertainty. *Mechanical Systems and Signal Processing,* Volume 149, pp. 1-22.

Zio, E., 2011. Risk importance measures. In: H. Pham, ed. *Safety and risk modeling and its applications*. London: Verlaag, Springer, pp. 151-196.

Zio, E., 2014. Integrated deterministic and probabilistic safety assessment: concepts, challenges, research directions. *Nuclear Engineering and Design,* Volume 280, p. 413–419.

Zio, E. & Podofillini, L., 2003. Importance measures of multi-state components in multi-state systems. *International Journal of Reliability, Quality and Safety Engineering,* 10(3), pp. 289-310.

Zwirglmaier, K. & Straub, D., 2016. A discretization procedure for rare events in Bayesian networks. *Reliability Engineering and System Safety,* Volume 153, pp. 96-109.

This doctoral thesis has been conducted under a convention for the joint supervision of thesis at Aalto University (Finland) and Politecnico di Milano (Italy)

Aalto-DD 104/2021

ISBN 978-952-64-0465-3 (printed)
ISBN 978-952-64-0466-0 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Aalto University
School of Science
Department of Mathematics and Systems Analysis
www.aalto.fi

BUSINESS +
ECONOMY

ART +
DESIGN +
ARCHITECTURE

SCIENCE +
TECHNOLOGY

CROSSOVER

DOCTORAL
DISSERTATIONS