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Accidents in the Civil Nuclear Sector and their Impact on Society

A Contribution to The Palgrave Handbook of Cybersecurity, Technologies and Energy Transitions

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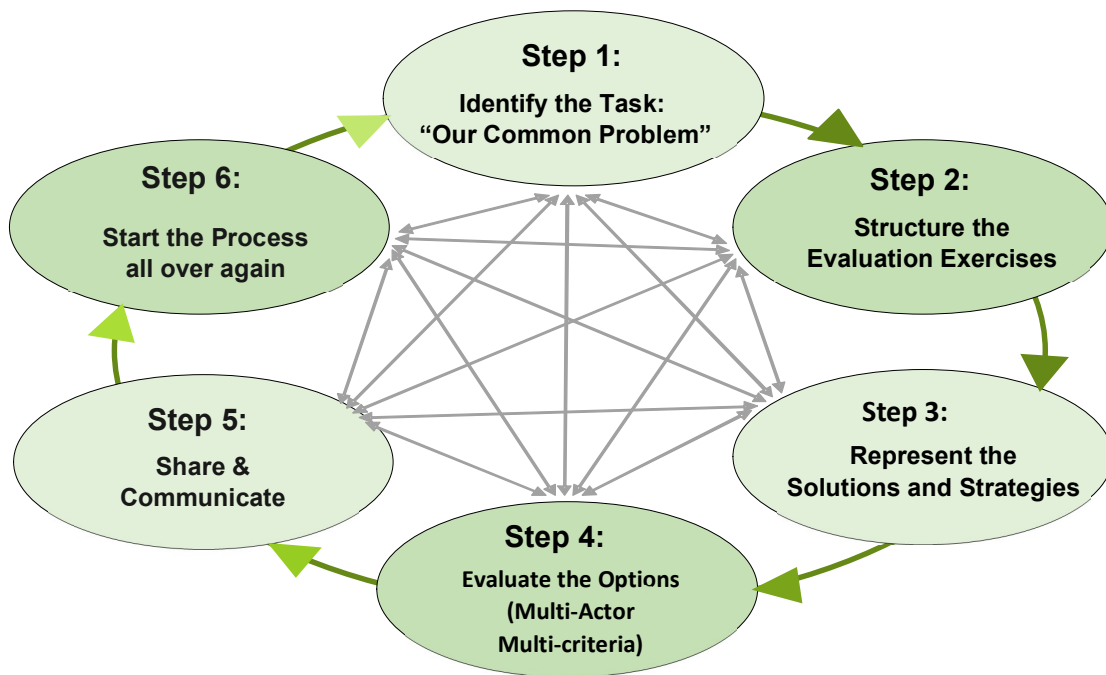
L’Association ePLANETe Blue is a non-profit NGO, constituted in France in 2015 (under the law of 1901). Its purpose is *“to promote reciprocity relations at all levels and anywhere, between persons and organisations active in the domains of environmental education and knowledge partnerships for sustainability.”*

Keywords:

Accidents, Action-research, AMORAD, Causality, Complexity, Controversy, Deliberation, Dilemmas, Entanglement, Foresight, Indeterminacy, Natural history, Post-Normal-Science, Radioactivity, Risk, Vulnerability, Wickedness.

*“Watchful, like men crossing a winter stream.
 Alert, like men aware of danger.
 Courteous, like visiting guests.
 Yielding like ice about to melt.
 Simple, like uncarved blocks of wood.
 Hollow, like caves.
 Opaque, like muddy pools.
 Who can wait quietly while the mud settles?
 Who can remain still until the moment of action? ...”*

[Tao Te Ching, Chapter XV]



Abstract:

We address the topic of accidents in the peacetime nuclear energy sector, as a study of foresight for risk governance. Starting from the question of methods for assessment (*ex post* and *ex ante*) of societal impacts of nuclear accidents, we also ask, reflexively, what are the lessons for (and impacts on) society of the practice of assessment of civil nuclear accidents? This subject is vast, so we adopt a “bottom up” approach via reflexion on the AMORAD project in France whose task (during 2013-2022) was to strengthen scientific knowledge about the ecological and societal impacts of an eventual nuclear power plant accident, particularly for the marine environment. In scientific terms, we need to have in mind a vast spectrum of causal chains, at multiple organisation scales in space and time — from atom to ocean (as it were). In societal terms, we must consider the “emergent reflexive complexity” of cultures, institutions and conventions as the embodiment, at a moment of time, of human consciousness, conjectures, motivations and action.

PART I presents the AMORAD experience and sets out our epistemological and methodological frame for the interfacing of theory, tools and terrains. Risk governance is premised on the interplay of several forms of causality — natural determinisms and human agency. The occurrence and severity of an accident may be contingent on small impulses (whether of natural or human origin); forecasts of the unfolding impacts of an accident, and of their significance to society, must address not only the “complexity” of natural processes but also the contingencies of human action.

Society is characterised not by unified purpose, but by the clash of many different wills: this is expressed as controversy and conflict. In foresight therefore, we situate ourselves as bit-part actors in an indeterminate cumulative causation. Not only are we dealing with processes where the “facts are uncertain”; above all we are engaged with people’s sense of danger and vulnerability in situations where there is little consensus about what most matters and why. We must represent, and simultaneously contribute to, a complex interplay between: (1) Biosphere processes including human societies, (2) Human perception and evaluation of significance of the Biosphere and its changes, (3) Imaginative projections into the future, (4) Real contributions by human action to Biosphere processes (these real actions being based in part on the fruits of foresight and conjecture), and (5) Adjustments to surprises, accidents, confrontations and reversals.

PART II sets out the method propositions made in AMORAD for the management of knowledge propositions about accident impacts and their significance (in environmental, economic and political terms), and discusses the spectrum of sources that we can mobilise. Rittel (1982) has provided a succinct formulation for a deliberative response to wickedness, suggesting that an analyst should act like a “midwife of problems”, helping to raise into visibility, “*questions and issues towards which you can assume different positions, and with the evidence gathered and arguments built for and against these different positions*”. In this spirit, we introduce the KerBabel Deliberation Matrix (KerDST) as an operational framework for societal capacity building. Knowledge propositions about accident impacts, whatever their character and their source, are situated simultaneously along three axes — what, who, and why — defining *the context of their mobilisation*. These axes are: (1) the environmental and economic sectors whose importance and vulnerabilities are to be adjudged; (2) the actors or stakeholders in controversies over the questions “What do we Know?”, “What do we fear?”, “What is to be done?”; and (3) normative considerations about what matters and why.

A foresight exercise thus involves all components of society, one way and another, both as sources and as judges of the pertinence of knowledge propositions. In Post-Normal Science terminology, this is the “*Extended Peer Community*”. In these terms, we show how to conduct a scoping study of the *ex-ante* vulnerability of a society at risk of a civil nuclear accident, as a multi-actor multi-criteria evaluation mobilising multiple perspectives on vulnerability. We set out corresponding typologies of “stakeholders” considered, alternately, in relation to (1) the sourcing (of “offer”) of knowledge propositions, and (2) the exploitation of (or societal “demand” for) knowledge propositions to communicate about what matters and why, so as to make them accessible as resources for risk governance capacity building.

In Conclusion, by presenting nuclear technology risk governance as *an unresolved controversy*, structured as an ongoing multi-site, multi-actor, multi-criteria evaluation, we portray the protagonists, including ourselves, as contributors to a collective knowledge resource. United, as a matter of (complex) fact, in a process of collaborative learning and capacity building, while nonetheless open to uncertainty as to whether and to what extent this unity is experienced inter-subjectively as a solidarity.

INTRODUCTION: IMPACT ASSESSMENT AND THE IMPACT OF ASSESSMENT

This chapter addresses the topic of accidents in the peacetime nuclear energy sector, as a case study in risk governance. We adopt a perspective in the risk analysis literature known as Post-Normal Science, which invites us to focus attention on questions of the quality of knowledge claims as a question of their *fitness for purpose* in situations where “*facts are uncertain, values in dispute, stakes are high and decisions urgent*” (Funtowicz & Ravetz 1990, 1993); De Marchi & Ravetz 1999; Funtowicz & Strand 2007; Douguet et al., 2009).

Starting from the question of methods and practices for the assessment (ex post and ex ante) of societal impacts of nuclear accidents, we also ask, reflexively, what are the impacts on society of the assessment of civil nuclear accidents? More particularly, what are the lessons for science practice and for our vision of science contributions to risk governance, that we can take from the experiences to date of scientists and wider civil society in this domain?

The chapter is structured in two main parts, respectively methodological (Part I) and empirical (Part II). That said, our approach will be dialectical, moving in a cyclical fashion between theoretical, methodological, and empirical considerations. In a short concluding discussion (Conclusion), we bring together some of the key strands of our argument.

PART I (sections §1 to §6) sets out our methodological frame. It introduces our preoccupation with the role of applied science for *informing action under conditions of high stakes and urgency*, in relation with the empirical and societal context of our case study — the AMORAD Project in France whose purpose during 2013-2022 has been to strengthen the scientific knowledge base about the ecological and societal impacts of an eventual nuclear power plant accident, as a part of preparedness for the eventuality of such an accident.

In a schematic way, we must meld together three approaches to action and knowledge. First, the vision of natural determinisms which informs most domains of science, epitomised for our purposes by (1a) the standpoint adopted by René Descartes in his meditations on method and on the conditions for “perfect knowledge”, (1b) the position of Pierre-Simon Laplace on the chasm between human limited knowledge and a perfect knowledge of the cause-effect mechanisms of the world around us, and (1c) the phenomena of “deterministic chaos” made famous by Jules Henri Poincaré with the case of the three-body problem. Second, the vision provided by Natural History as it has emerged since the 18th century, exemplified by (2a) the encyclopaedic writings of Buffon and Humboldt, (2b) the synthetic view of The Biosphere developed by Vernadsky, and (2c) contemporary open systems theory with its accents on emergent structures and interactions across multiple levels of organisation, and indeterminate system-environment coevolution. Third, the science of decisions which takes as axiomatic (3a) the phenomenon of human free will or volition, (3b) the problematics of individual dilemmas and controversies of collective choice, and 3(c) the reflexivity inherent in the recursive movements between speculation about possible futures and justifications for current action whose intent is to influence these futures.

In other terms, we develop our approach to accident impact appraisal through consideration of the interplay of several forms of causality — natural determinisms on the one hand, and human agency on the other hand. This interplay is complex and gives rise to several paradoxes, or antinomies, that are at the heart of risk governance. What, we ask, can we propose as ways forward for science and risk governance when the stakes are high, when we have very incomplete knowledge about the salient relations of cause-and-effect, when outcomes may be highly sensitive to small impulses whether of natural or human cause, when there is little consensus about what is right and important, and when our (incomplete) knowledge at any moment in time is incessantly being overtaken by both necessity of action and inevitability of the passage of events?

That the stakes of a major nuclear accident are high is a solid starting point, in the sense that, if an accident occurs, the likelihood of devastating effects is not in dispute. The stakes are high also in the sense that, in risk governance, real decisions with weighty consequences are being taken — sometimes with urgency — on the basis of imperfect knowledge, *whose purposes and effects (whether intended and unintended)* — are nonetheless to modify the life conditions and the hopes for prosperity of the members of present (and future) society. We seek to characterise the impacts of an accident not simply (1) in terms of the modification of environmental conditions (which is already complex enough as a scientific challenge), but also, (2) to form judgements about the significance of these modifications for human societies, and more particularly (3) to inform actions whose intent is to influence these effects and their significance. We are not just asking how an accident might impact on the life conditions and the hopes for prosperity of our present and future societies; we are intending that this knowledge will allow us to act both today and tomorrow, to **improve our preparedness in the event of a future accident**. We believe in our agency in the world, and we are developing foresight about possible futures as an exercise in **collective capacity building**.

PART II (sections §7 to §11) exploits our AMORAD Project experience as a case study to make method suggestions on *ways of doing science as if wickedness matters* (cf., O'Connor & Douguet 2024), in this spirit of collective capacity-building. The wickedness of nuclear accidents has several facets.¹ Not only are we dealing with complex interdependent processes where the “facts are uncertain” (both *ex ante* and *ex post* relative to an accident); but, more importantly, we are engaged with people’s sense of vulnerability. The cocktail of (disputed) facts, speculation, and uncertainty about outcomes works to heighten the sense of exposure to danger, the risks to health and to life, the fears of loss of livelihoods and other opportunity. It is necessary to act (and to react) where the justifications for action cannot be resolved by appeals to “optimisation” or to “more knowledge”. We need a method of investigation, synthesis, restitution and mobilisation of knowledge about past and (hypothetical) future accidents that places on centre stage this experience of vulnerabilities, and that admits the deeply incomplete character of our knowledge while nonetheless positioning it as a societal resource for orienting action.

Rittel (1982) has provided a succinct formulation of the deliberative response to wickedness, suggesting that an analyst needs to act like a “*midwife of problems*”, helping to raise into visibility, “*questions and issues towards which you can assume different positions, and with the evidence gathered and arguments built for and against these different positions*”. To this end, we introduce the KerBabel Deliberation Matrix (or KerDST) as an on-line tool for the mobilisation of knowledge propositions by, or on behalf of, a community of users engaged in a complex evaluation exercise. This tool provides a framework for a cataloguing process whose effect is to situate knowledge propositions, whatever their sources, along three axes defining *the context of their mobilisation*. In generic terms, the three axes are:

- WHAT? — The situations, sites and actions whose quality or acceptability is to be judged.
- WHO? — Relevant actors or stakeholders in controversies over the question “What to Do?”.
- WHY? — Relevant criteria of performance, quality or acceptability.

After a succinct presentation of the main features of the KerBabel deliberation support tools, we lay out the propositions made in AMORAD for the cataloguing of knowledge propositions about accident impacts. This involves the mobilisation of several distinct frames of multi-actor multi-criteria deliberative evaluation in order to provide, in a composite way, a synthetic vision of the impacts of a (possible) accident and of their significance (in environmental, economic and political terms) for society.

¹ We use the term “wicked problems” in the spirit of early formulations from soft systems and territorial planning literatures (e.g., Rittel & Webber 1973; Rittel 1982; Checkland 1980; Checkland & Scholes 1990), addressing situations that resist a unique formulation of “What is the problem?” and that are characterised by controversy around “What is a solution?” For recent literature review, see Head (2019) and Head (ed., 2022).

We set out several different conventions for the typology of “stakeholders” engaged in a process of integrative assessment, and our method for classifying knowledge propositions simultaneously on the basis of (1) their sourcing (the “offer” of knowledge propositions), and (2) their exploitation to communicate about *what matters and why in the eyes of different stakeholders* (the societal “demand” for knowledge propositions), so as to make them accessible as resources for risk governance capacity building.

Examples of classification axes for the sourcing of knowledge propositions, are: (a) historical and potential nuclear accident sites, in France and elsewhere in the world; (b) the broad disciplinary domains of human understanding across the sciences and humanities; (c) the distinct forms and levels of system organisation associated with different disciplinary domains; and (d) demarcations of stakeholder classes and institutions.

Finally, we will discuss, though only briefly for space reasons, the spectrum of sources that we exploit and the multiplicity of organisation levels in physical, biological and societal systems at which (and between which) cause-and-effect relations must be portrayed.

PART I

Action-Research: Knowledge of Being and Becoming

§1. The AMORAD Project

AMORAD was a research project funded by the French National Research Agency (ANR) during 2013-2022, aimed at improving dispersion forecast and impact assessment of radionuclides in the environment with the intention to support post-accident risk management. It responds substantively to the awakening of the French state to the pertinence of knowledge in a precautionary sense, for preparedness for an eventual nuclear plant accident. As such, it provides a remarkable opportunity to extend our exploration of the roles of collaborative learning processes in wicked problem structuring (Douguet, Lancelleur & O'Connor 2024).

The AMORAD project was coordinated by the French IRSN (a publicly funded agency with statutory responsibilities for research and expertise in nuclear technology risks and safety), and involved thirteen research partners, including five teams from French universities (Toulouse, Toulon, Bordeaux, Versailles-Saint-Quentin-en-Yvelines, Pau and Pays de l'Adour), one Japanese university (Tsukuba), and five public and private undertakings (IFREMER, CEA, ANDRA, BRGM, EDF, CLS). The work programme brought together specialists of several scientific disciplines (oceanography, chemistry, biology, radioecology), and also two teams with expertise in decision sciences — including ourselves (ecological economics).

As stated on the IRSN website,² the AMORAD Project had as its overall objective “... to answer the key question of how to accurately assess the impact on humans and the environment of a release of radioactive substances.” In more operational terms, the stated goal was “... to optimize the models used to predict radionuclide dispersion in the environment and to assess their impact on two compartments of the biosphere: the marine environment and terrestrial ecosystems (including surface water)”, with special attention also being given to the ocean-continent interface.

The project thus focussed on two major compartments of the Biosphere — sea and land — making it possible to investigate radionuclide fluxes between them and at their interface.³ Studies were conducted in several parts of France, the Ukraine and Japan, with several test areas set up on land contaminated by the Fukushima accident. A large amount of in-situ data has been collected, which has been used to calibrate and validate various modelling tools, designed to predict what happens to

² The main IRSN website is: <https://www.irsn.fr/recherche/projet-amorad>. An overview in English is available at <https://en.irsn.fr/research/amorad-project> [accessed on the 27 April 2024], which we exploit directly here. Some aspects of our presentation are adapted from chapter 9 of the doctoral thesis by our colleague Bastian Tran (2019).

³ **Appendix ‘A’** provides a short description of the project, with its two axes CONTI and MARIN. The initial proposal had distinguished four axes, each focusing on a compartment of the biosphere (atmospheric, continental, biological, marine). These were: ATMO: atmospheric dispersal of radionuclides, transformations and transfers (sediments) under dry and wet conditions; CONTI: multi-environment modelling and operational valorisation (decision-making), erosion in watersheds, biogeochemical cycles; ECOTOX: evolutionary impact of radiations on non-human organisms and populations; and MARIN: dispersal of radionuclides in water bodies, processes at the continent/ocean interface, transfers of radionuclides to trophic chains as well as ecosystem and human activities sensitivity and vulnerability to these transfers. Discussions with funding bodies led to focus on CONTI and MARIN as the domains most urgently in need of advancement. In reference to ATMO, work since the first nuclear bomb explosions and later Chernobyl has addressed atmospheric dispersal of radionuclides and subsequent transformations and transfers. As regards ECOTOX, knowledge remains incomplete about impacts of radiation (including environmental exposure and ingestion) on non-human organisms and populations, but the more critical gaps relate to the complex and larger-scale environmental processes leading to this exposure.

radionuclides following releases into the sea or the atmosphere, and how they are redistributed. The intention was that, based on scenarios and the various case studies, these models should be used to develop recommendations for strategies to monitor environments and resources, to reduce vulnerability of human (and other populations), and to manage contaminated lands and water in the medium to long term.

Our own research group was engaged to contribute to the BIO-ECO work package within the MARIN axis. The MARIN axis was itself subdivided into four work packages:

- ◆ HYDRO, for hydrodynamic dispersion models through the tracking of radio markers.
- ◆ SEDI, for process analysis and modelling of sedimentary transports of radionuclides.
- ◆ BIO-ECO, focussed on radionuclide transfers in marine trophic networks, and in particular the ecological and economic sensitivity of the coastal area to these transfers.
- ◆ DeMAD, a transversal component for developing decision support tools.

The task assigned to us (the KerBabel team, based in 2013 at the University of Versailles St-Quentin-en-Yvelines) was, in collaboration with the IRSN (the project coordinator), to provide a vulnerability analysis for coastal ecosystems and human activities potentially impacted by the dispersal of radioactive materials after a nuclear accident. This imposed, in effect, the requirement to build a method for responding to the following question: *What would be the significance for socio-economic activity, of changes in the biophysical environment that might be provoked by a nuclear accident?*

§2. Risk Governance: A Tale of Two Causalities

The ambition of the AMORAD project was not just to provide “foresight” about possible impacts of an accident, but also to contribute methods and tools that can support decision-making in a post-crisis context. While the project's apparent structure was to separate each biosphere compartment (atmospheric, continental, marine...), the question of transfers from one compartment to the other was indeed central to the project. It was well understood by the project partners that, in order to appraise the significance for socio-economic activity of changes induced in the biophysical environment, we need to have in mind the whole spectrum of causal chains, at multiple organisation scales (in space and time), and also the full spectrum of possible societal responses.

For example, in the MARIN programme meticulous work was carried out to characterise (i) radionuclide dispersal in river, estuary and marine water bodies, (ii) transfer processes at the interfaces (continent/sediments), and (iii) transfers of radioactive materials to trophic chains. And then, to characterise the vulnerability of impacted ecosystems and associated human activities, it is necessary to appraise not only the effects on ecosystems but, more particularly, the diversity of the “services” provided by the biophysical environment to human societies.

In very general terms, environmental and ecosystem services can be divided into four classes. These are: the inflows of natural resources (including energy) to society; the outflows of waste materials and energy to the environment; the biophysical environment as an object of sensory appreciation (across the 5 senses); and the physical world as a life-support system. For a given territory envisaged as vulnerable to a nuclear accident, we must make an appraisal of the different services across these four broad categories, estimating the impact on society of their disappearance or diminution. We must also consider in what ways human society might respond. For, it is not a question simply of predicting an influx or ingestion of radioactive materials. In what ways can the exposure of a territory, an ecosystem or an organism to fluxes of contaminated materials be reduced?⁴ Can ingestion or other

⁴ Historically, the French steering bodies for *ex post* management of nuclear accidents (CODIR-PA) make the distinction between two main classes of territories: areas for population protection where priority actions are engaged with the purpose of reducing the doses the inhabitants might otherwise receive; and areas for

uptake of radioactive materials be prevented? Can or should the human (and animal) populations of a zone be evacuated? Should the exploitation of water, and of biological resources (for food and for other uses) be curtailed? What rehabilitation programmes (for buildings, soil, water and living populations) might be envisaged? Over what timescales? And so on.

The MARIN axis of AMORAD thus considered a multiplicity of physical processes within and between all compartments of the environment. Relevant spatial and temporal resolutions for observation and modelling purposes, range from micrometres and hours (for example, in the case of soil-to-plant transfers), to thousands of kilometres and several years (in the case of marine food chains).⁵ Moreover, an essential ambition of the project was to exploit the knowledge that has been or can be gained from the Fukushima misfortune, in transfer to the French context. This implied measurement and modelling activities in the Fukushima area and ocean, but more particularly a better understanding of the specifics of French contexts. Four zones in France were retained as objects of analyses:

- ◆ The English Channel, in recognition of the presence of a major fuel reprocessing facility and of several nuclear power plants on the Normandy coast;
- ◆ The Gulf of Gascony, on the French Atlantic coast, which receives outflows from the Gironde River which hosts several nuclear power plants;
- ◆ The Gulf of Lion, which receives outflows from the Rhône River (which hosts several nuclear powerplants) into the Mediterranean Sea characterised by low tidal fluctuations;
- ◆ Toulon's harbour, which is the main French naval base.

This vast disciplinary and geographical diversity has provoked a vivid awareness of the impossibility of obtaining a simultaneously precise and complete representation of the myriad causal sequences from the point of an accident to air, aquatic and terrestrial ecosystems eventually impacted by radioactive contamination. It has highlighted a paradox at the heart of a scientific approach to technology risk governance, that we have already set out in our Introduction. AMORAD has sought to respond to the challenge of improved scientific knowledge as a resource for informing action under conditions of high stakes and urgency. A cogent framing of this task requires careful articulation of two distinct categories of causality — each giving rise to corresponding concepts of determination and indetermination — and of the interplay of these two distinct causalities.⁶

- ◆ On the one hand there is causality in the sense exploited in most fields of science, including in AMORAD, with the expression “*cause-and-effect*” (or causal sequence) whereby a particular event or outcome is understood to be determined by a set of pre-existing conditions. This vision of causality relies on notions of

reinforced surveillance where specific monitoring of food and agricultural products would take place. There is a continuum from outright evacuation (to the extent possible), through restrictions on specific resource uses and activities, to efforts at care and rehabilitation, to ongoing monitoring of radioactivity levels for different types of radionuclides in different types of living and non-living matter. These points become important for the elaboration of ex post scenarios of post-accident adaptation.

⁵ For examples of scientific work in the context of AMORAD, see the selection of publications on the HAL-IRSN website, at : <https://irsn.hal.science/search/index?q=AMORAD>. The purpose of the present article is not to review this scientific work, simply to locate it in our context of societal risk governance capacity building.

⁶ Many formulations exist of the antinomies [that is, seeming contradiction between two apparently equally valid principles, or between inferences drawn from such principles] arising from the coexistence of different orders of causality. In our context, we have a pragmatic need for a framework that reconciles (1) a scientific vision of determinate cause-and-effect regulating natural phenomena, with (2) notions of free will at the level of human intention, agency and (more or less unintended) outcome. On the history of thought on notions of freedom (and free will) and determinism (including chance and necessity), see Proops (2021) with reference to the Kantian antinomies; Egginton (2023) with an interweaving of Heisenberg (and quantum indeterminacy) with Borges (on dilemmas of action); and Boulnois (2021) retracing concepts of freedom in the history of thought from Aristotle to the present day. For our purposes, as will be seen, it is necessary simply to insist on two classes of causality — natural lawfulness and human volition/agency — as coexisting and in complementarity, without further arbitrating on the finer points of their antinomies and compatibilities.

the lawfulness of natural phenomena, epitomised by principles of invariance — such as laws of conservation (of energy, of mass, of momentum, of atoms, in application to different classes of phenomena) — which characterise objects and their interactions.

- On the other hand, there is causality in the sense of the “agency” of conscious beings, notably humans, who experience the capacities of volition and choice — that is, of engaging action along one pathway while renouncing the opportunity of other pathways.

The inherent complexity of risk governance stems from the ways that we must exploit both these senses of cause-and-effect, simultaneously and alternately, in a sort of tango of partial determinations and indeterminacies. Notably, for example, scientific teams may engage in exercises of “deterministic modelling” of natural processes (including stochastic or probabilistic formulations) in order to inform human choices whose avowed purposes are to influence these processes. In practice, we must take on board the two classes of causality — natural law and human agency — and reflect on the ways that, in risk governance foresight exercises, we meld the two together.

§3. Natural Causality and Imperfect Knowledge: From Descartes to Laplace

As a pathway to the modern understanding of causality in (complex) natural processes, it is useful to revisit some key moments along the highways and byways of determinism. Jerry Ravetz (2015), in his essay “Descartes and the rediscovery of ignorance”, reminds us that one of the core motivations in Descartes’ writings was to provide the means — that is, elements of method — to arrive at forms of knowledge “*highly useful in life*”. That is,

“... by means of which, knowing the force and action of fire, water, air, the stars, the heavens, and all the other bodies that surround us, as distinctly as we know the various crafts of our artisans, we might also apply them in the same way to all the uses to which they are adapted, and thus render ourselves the masters and possessors of Nature...”

Knowledge is a resource for action. This gives rise to an obvious antinomy at the heart of Descartes’ reasoning. On the one hand, there is a brand of knowledge — Descartes’ “*perfect knowledge*” — that underpins the hope and confidence in the instrumental value of knowledge as a means to achieve determinate results. On the other hand, there is the presumption that humans as “*masters and possessors of nature*” are acting freely, with purpose and agency. How does Descartes reconcile the two causalities, to link human knowledge to masterful action? He doesn’t; or, only very crudely. At the heart of the famous Cartesian mind/body dualism, is the presumed separability of two domains of causality. Processes in Nature are lawful; but humans can choose freely to intervene in these processes, modifying the play of natural forces, and thereby influencing the outcomes.

This dualism is powerful and has greatly influenced centuries of philosophy, politics, science, and technology up to the present day. Nonetheless, some huge grey areas remain, as “*imperfection*.” Famously, Descartes defines perfect knowledge in terms of doubt or, more precisely, in terms of the grounds or basis available for expressing doubt. In a passage distinguishing lesser grades of conviction relative to perfect knowledge, he writes:⁷

“I distinguish the two as follows: there is conviction [persuasio] when there remains some reason which might lead us to doubt, but knowledge [scientia] is conviction based on a reason so strong that it can never be shaken by any stronger reason.”

Affirming perfect knowledge requires, thus, that it would be “*impossible for us ever to have any reason for doubting what we are convinced of*”. This marks an extremely high standard of justification. It is of very limited applicability. In practice, Descartes acknowledged (as cited in Newman, *ibid.*),

⁷ We draw here on the synthetic review article by Lex Newman (2019), “Descartes’ Epistemology,” which is densely referenced to primary sources of Descartes, notably in English translation.

“... since the pressure of things to be done does not always allow us to stop and make such a meticulous check, it must be admitted that in this human life we are often liable to make mistakes about particular things, and we must acknowledge the weakness of our nature.”

With the benefit of hindsight, this frailty of human nature, the liability “to make mistakes about particular things”, has rather devastating consequences for Descartes’ hopes for us as masters and possessors of Nature. Across nearly four centuries since publication of the *Discours de la Méthode* by Descartes (in 1637), our learning about Nature is correlated with a deepening and widening of our interventions in nature — in geophysical process, in ecosystem functioning and in the components of life itself — but not with a uniform improvement in predictability. The vulnerability to mistakes relates not only to imperfect knowledge of what is (that is, the present state of things), but, more particularly, to errors and imperfections in our knowledge what might come to be in the future. It relates not only to the forces and actions (and their effects) governed by natural laws, but also to our knowledge about human intentions, actions, and effects. We are capable today of intervening in organisation at the scale of atoms (nano technologies, quantum computing, nuclear fission and fusion), of molecular and cellular structures (including genetic heritage and their expression, e.g., gene splicing and cloning technologies), and of planetary atmosphere and ocean current circulation systems. Yet, oftentimes, the unintended so-called “side-effects” come to be far more significant than the original design (O’Connor 2009).

Our AMORAD case-in-point is the “fall-out” of radioactive materials after a nuclear power plant accident, where the hazard management challenges extend over a very much longer time horizon, and across much more dispersed spatial contours, than the planned spans of power generation and electricity consumption themselves.

If knowledge that is “*highly useful in life*” is conceived on the basis of precise understanding of relations of cause and effect, something is nonetheless missing in Descartes’ formulation. The pragmatic enquiry into particular causes and effects has, across the centuries, opened out onto much vaster metaphysical questions of *causality*, where — one way and another — philosophical and religious preoccupations with the existence (or not) of an underlying *determinism* (or not) of actions and events have tended to bias scientific enquiry into the richness of natural phenomena and processes.

The German mathematician and philosopher Gottfried Leibniz, writing at the end of the 17th century (that is, some 50 years after Descartes), had insisted on the primordial status of cause-and-effect as a basis for human reasoning. He espoused the principle of sufficient reason, meaning by this, that “*nothing happens without its being possible for someone who understands things well enough to provide a reason sufficient to determine why it is as it is and not otherwise*” (Leibniz, 1714, p. 262). In these terms, he further imagined mathematics as the instrument or metaphor for “*a prophetic intelligence that could see the future as in a present mirror*”.⁸

One hundred later, the French mathematician Pierre Simon de Laplace retook Leibniz’ (and others’) arguments in the spirit of the times (cf. van Strien 2014), but in remarking a fundamental difficulty. In a famous passage of his *Essai Philosophique sur les Probabilités* (written about 1794 and published in 1814), which is rarely cited in full, Laplace writes:

... Current events are connected with preceding ones by a tie based upon the evident principle that a thing cannot come to existence without a cause which produces it. This axiom, known as the principle of sufficient reason, extends even to the most indifferent acts ...

... We ought then to regard the present state of the universe as the effect of its anterior state and as the cause of the one which is to follow. Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings

⁸ As cited by Funtowicz & Guimarães Pereira (2015) in their essay on “Cartesian dreams”, in: Guimarães Pereira & Funtowicz (eds., 2015). Marij van Strien (2014) in a discussion of the origins and character of Laplace’s view on determinism, points to philosophical influences such as Leibniz in complement to the mathematical determinism expressed in 19th century classical mechanics.

who compose it -- an intelligence sufficiently vast to submit these data to analysis -- it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes....

... The human mind offers, in the perfection which it has been able to give to astronomy, a feeble idea of this intelligence. Its discoveries in mechanics and geometry, added to that of universal gravity, have enabled it to comprehend in the same analytic expressions the past and future states of the system of the world. Applying the same method to some other objects of its knowledge, it has succeeded in referring to general laws observed phenomena and in foreseeing those which given circumstances ought to produce. All these efforts in the search for truth tend to lead it back continually to the vast intelligence which we have just mentioned, but from which it will always remain infinitely removed.

Laplace seems here to embrace a vision of an underlying determinism based on the ubiquity of causes. On the other hand, he does not set the perfection of Leibniz' mathematical mirror as the reference point for human enquiry. Rather he declares that such a universal intelligence, if it exists, would be a capacity "from which [the human mind] **will always remain infinitely removed**".

In espousing this aporia, Laplace drives a wedge between predictability in principle (applying the principle of sufficient reason) and (un)predictability in practice. He reopens a Pandora's box with, on the one hand the question as to what might be hoped, in practical terms, from the enquiry into causes; and, on the other hand, the question of how to advance human knowledge when, or to the extent that, we do not have adequate access to the truth about causes.

It is well-known that, when writing this passage, Laplace was setting the scene for the compilation of his lessons on probability as a field of mathematical and descriptive method that was to be applied, quite precisely, where the **absence** of access to complete knowledge on objects, their properties and their interactions meant that it was impossible to derive "laws of motion" from consideration of the real causes and effects. It has become commonplace, during the 200 years since Laplace taught and wrote, to affirm that, in the absence of detailed knowledge (or, indeed, any knowledge at all) about cause-and-effect relations, one can (or should?) adopt a probabilistic approach that, as popularly understood, substitutes statistical correlations for causality.

This line of reasoning has been raised to the status of dogma in some domains of risk analysis and decision theory.⁹ Probabilistic approaches are nonetheless only one branch in the spectrum of possibilities for science-based risk governance practice. Their adequacy (fitness for purpose), or not, depends on several factors. First, on the adequate identification of pertinent classes of objects, events, trajectories and transformations; and secondly, on the validity (which often can be appraised only after-the-fact) of hypotheses about the "stationarity" of the relevant systems and their "probability distributions". The precariousness of these requisite conditions is highlighted by a scientific tradition running in parallel with the Leibniz paradigm of mathematical determinism: that of Natural History.

§4. Natural History and the Dialectics of Stability and Instability

The field of Natural History is associated notably with the encyclopaedic works of Buffon (*Histoire Naturelle*, in 44 volumes spanning 1749-1804) and of Alexander von Humboldt (*Kosmos*, 1845-1862)¹⁰. The works of these two brilliant men constituted, each in their own way, attempts to bring together

⁹ Our purpose here is not to argue for or against probabilistic approaches, which — as any person using GPS systems to navigate from A to B on modern roads — have undoubted pertinence while also being fraught with perils. We simply situate the Laplacian tradition of probabilistic analysis in the wider landscape of risk governance action-research tools.

¹⁰ On Buffon's *Histoire Naturelle*, see: https://en.wikipedia.org/wiki/Histoire_Naturelle. On the life and work of Humboldt, see: https://en.wikipedia.org/wiki/Alexander_von_Humboldt.

scientific knowledge from all known fields, in a unified vision of the orderliness (or lawfulness) and the diversity of the physical world. This vision, developed by a triangulation of acute empirical observation, openness to the ideas of contemporaries and past scholars in all fields, and comparison made possible by extensive travelling and documentary exchange, reaches a later apotheosis in the synthetic vision of evolving geo-bio-chemical systems in the Biosphere proposed by Vernadsky (1929/2002).

In the tradition of Natural History there is, on the one hand, the recognition of regularities and patterns that justify notions of natural laws; and, on the other hand, a unique unfolding of phenomena with distinct organisational forms, at multiple scales in space and time. The known material universe is in an incessant process of Becoming. As expressed in the seminal encyclopaedic works of Buffon and Humboldt, scientific knowledge is organised around distinct phenomenal domains, with their distinctive disciplines, inasmuch as regularities of particular type or at a chosen organisational level are able to be discerned while abstracting away from the detail of the other modes or levels.

Much later, system theorist Herbert Simon (1973, pp.26-27) has employed the concept of the “near-decomposability” of different orders of organisation and interaction of component parts:

Scientific knowledge is organized in levels, not because reduction in principle is impossible, but because nature is organized in levels, and the pattern at each level is most clearly discerned by abstracting from the detail of the levels far below.

As argued by Simon (ibid.), where there is only weak inter-level coupling, the emergent entities at a given level can often be described, and their interactions analysed, without explicit reference to lower-level detail. This correlates with the distinct scientific disciplines such as sub-atomic physics, chemistry, biology, ecology; and the argument can loosely be applied also to the various environmental and Earth sciences.

But, as a corollary, the “silo” approach to knowledge remains viable **only as long as there is no significant influence (interference, invasion, intrusion) coming from other levels**. And nature is, as Simon puts it, only nearly-decomposable. The story of science neither starts nor finishes with the elucidation of tidy phenomenological laws describing separate layers of observable regularities. On the contrary, the decisive difficulties of science around predictability and knowledge quality arise from **the entanglement of different organisational levels and modes of interaction**, an entanglement within which human agency plays its full part both by design and by inadvertence.

The Natural History vision of a world-in-becoming, with multiple layers of (relative) stability, is in a clear tension with the “Laplacian” paradigm, exemplified by classical mechanics, of physical phenomena as determined and predictable in accordance with cause-and-effect relations describable with mathematical laws. A reconciliation can nonetheless be achieved, at the price of a certain relaxation of the Leibnizian dictum of “sufficient reason”. We can trace a pathway for this reconciliation through the arguments of the mid-19th century physicist James Clerk Maxwell and of the late 19th century mathematician Henri Jules Poincaré.

Maxwell, in an essay delivered in 1873 at Cambridge University, reflected on the insights that might be taken from science for the perennial philosophical questions of free will and determinism. Insisting (in resonance with Laplace) on the absolute impossibility of a complete knowledge of all bodies and their interactions, he seeks nonetheless a qualitative understanding of phenomena “by the consideration of stability and instability”. In so doing, he provides a clear anticipation of the mathematical domains now referred to as bifurcation theory and deterministic chaos; and he also anticipates on the limits and ambiguities of the “determinism” proposed within chaos.

When the state of things is such that an infinitely small variation of the present state will alter only by an infinitely small quantity the state at some future time, the condition of the system, whether at rest or in motion, is said to be stable; but when an infinitely small variation in the present state may bring about a finite difference in the state of the system in a finite time, the condition of the system is said to

be unstable. It is manifest that the existence of unstable conditions renders impossible the prediction of future events, if our knowledge of the present state is only approximate, and not accurate.¹¹

Maxwell cites phenomena from several different domains of physics, including optics and industrial chemistry.¹² Two decades on, Poincaré (1890) corroborated Maxwell's diagnosis with a mathematical investigation of the dynamics of systems having only a small number of degrees of freedom. Ushering in the field now known as deterministic chaos, he provided a mathematical demonstration of instability — that is, a very high degree of sensitivity of systems pathways to initial conditions and to the way in which they are set in motion — within systems that are formulated as perfectly deterministic. Moreover, in his reflexions on scientific discovery and explanation (Poincaré 1908, English translation by Francis Maitland 1952, p.68), he displayed an acute sensibility to the deeper questions of determinism.

*If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment. But, **even if it were the case that the natural laws had no longer any secret for us [italics added]**, we could still only know the initial situation approximately. If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible ”*

On the surface, this is the so-called butterfly effect,¹³ by which the flapping of a butterfly's wings on one side of the planet might provoke a hurricane thousands of miles away. But the examples and arguments provided by Maxwell and Poincaré show that there is an issue deeper than the sole property of “instability”. Poincaré writes carefully, with an allusion to Laplace's demon, that, **even if it were the case that the natural laws had no longer any secret for us**, in practical terms we can only know an initial situation approximately, and so prediction becomes impossible. This precaution is not innocent. Because, for any chosen phenomenal domain, the deeper questions must be asked,

- ◆ Are we adopting deterministic chaos as an ontological hypothesis (viz., as a set of mathematical relations considered as descriptive of reality and which, for certain ranges of values, exhibit “extreme sensitivity to initial conditions”)?
- ◆ Or are we adopting deterministic chaos as an explanatory desideratum in a heuristic sense, while admitting that the underlying reality is more complex and/or incompletely known?

Looking across the disparate phenomenal domains where the mathematics of deterministic chaos have been applied, it is the second (and not the first) of these propositions that is the general rule. This is of paramount importance. Because, firstly, it cannot be excluded that features that are masked or smoothed by mathematical modelling at a given phenomenological level, might nonetheless be

¹¹ The complete essay by Maxwell (1873) is reproduced in Chapter XIV “Last Essays at Cambridge” in the comprehensive biography by Campbell & Garnett (1882). The insights of Maxwell on instability and on the problem of free will and determinism have been pointed out by Hunt & Yorke (1993).

¹² The example from optics demonstrates the fusion of scientific conceptual rigour with didactic clarity: “In the refraction of light, the direction of the refracted ray depends on that of the incident ray, so that in general, if the one direction be slightly altered, the other also will be slightly altered. In doubly refracting media there are two refracting rays, but it is true of each of them that like causes produce like effects. But if the direction of the ray within a biaxial crystal is nearly but not exactly coincident with that of the ray-axis of the crystal, a small change in direction will produce a great change in the direction of the emergent ray. Of course, this arises from a singularity in the properties of the ray-axis, and there are only two ray-axes among the infinite number of possible directions of lines in the crystal; but it is to be expected that in phenomena of higher complexity there will be a far greater number of singularities, near which the axiom about like causes producing like effects ceases to be true.”

¹³ The term was coined by Edward Lorenz, who, in the early 1960s, demonstrated deterministic chaos properties in mathematical models of weather systems. An introduction to the mathematics and domains of deterministic chaos, including fractals (self-similarity), non-linear systems and bifurcation theory, and various extrapolations to societal phenomena, is provided at: https://en.wikipedia.org/wiki/Chaos_theory

contributing in a significant way to the initial conditions and to the impulsions for the system's motion. Evident examples are chemical impurities provoking sickness or death, the emergence of a virus provoking a pandemic, or a tweet on a social network setting off a diplomatic storm. And, secondly, in the physical world we are most often dealing with many bodies (variously described as systems or sub-systems) that are open to and interacting with each other. If one system taken to be characterised by deterministic chaos, is influencing another system also characterised by extreme sensitivity to initial conditions (etc.), then there is a "second-order" instability and substantive prediction becomes doubly impossible.

Maxwell (op.cit.), by situating himself not as an external observer representing a system trajectory, but as an actor at a particular time and place, interacting with the objects around him, had grasped the significance of all this.

*It is a metaphysical doctrine that from the same antecedents follow the same consequents. No one can gainsay this. **But it is not of much use in a world like this, in which the same antecedents never again concur, and nothing ever happens twice [emphasis added]***

*.... For example, the rock loosed by frost and balanced on a singular point of the mountain-side, the little spark which kindles the great forest, the little word which sets the world a fighting, the little scruple which prevents a man from doing his will, the little spore which blights all the potatoes, the little gemmule which makes us philosophers or idiots. Every existence above a certain rank has its singular points: the higher the rank, the more of them. At these points, **influences whose physical magnitude is too small to be taken account of by a finite being, may produce results of the greatest importance [emphasis added]**.*

Without in any way neglecting natural lawfulness, Maxwell shifts the focus of attention away from mechanics and towards Natural History, and simultaneously towards the Humanities. He opens a door towards a methodologically coherent interfacing of **two orders of causality**, proposing natural causality and human agency as complementary forces in a methodologically unified science of Becoming.

"No one, I suppose, would assign to free will a more than infinitesimal range. No leopard can change his spots, nor can anyone by merely wishing it, or, as some say, willing it, introduce discontinuity into his course of existence. [Nonetheless, ...] In the course of this our mortal life we more or less frequently find ourselves in a physical or moral watershed, where an imperceptible deviation is sufficient to determine into which of two valleys we shall descend.

§5. A Concatenation of Causalities

This indeterminacy of Becoming does not mean that nothing can be said about system trajectories. In the physical world, for each class of phenomena, the so-called chaotic behaviours are bounded in various ways, including conservation laws and invariance principles at relevant scales (energy, momentum, etc.). What it means is that an approach uniquely in terms of lawful regularities, seeking predictability, is deeply insufficient for scientific work in the conditions of ordinary life. On the one hand there is indeed natural lawfulness. On the other hand, there is "emergent complexity" (O'Connor 1989, 1994; Funtowicz, O'Connor & Ravetz 1997; Funtowicz & O'Connor 1999), marked by the co-dependency and indeterminacy of coupled systems, open and thereby vulnerable to each other, interacting in many different ways, such that "**the same antecedents never again concur, and nothing ever happens twice**".

Methodological precepts for analysis in such a perspective of complexity have been presented in a synthetic way by O'Connor (1991). Drawing explicitly on Simon (1973), Wheeler (1977), Morin (1977, 1980), Stengers (1986, 1987), and a wide spectrum of science, system theory and philosophical domains, he proposes in very condensed terms:

- (i) Many distinct layers of phenomenal laws and regularities can be discerned. No level is more fundamental than any other, but the many layers depend on each other — Including human

consciousness and contributions in nature — and give rise to each other as a codependent evolving whole.

(ii) Broadly speaking these layers can be correlated with distinct sorts of interactions between components of larger ensembles, ranging across the subatomic and intermolecular to the gravitational dynamics of galaxies, through prey-predator interactions, self-organisation, cognition and communication processes of biological populations and human societies.

(iii) At any level of analysis, in the analysis of cause-and-effect, the keynote is the incompletely predictable interplay of a system with its heterogeneous environment. Any system, or component sub-system under analysis is considered as preserving a degree of contingency — freedom or indeterminacy — as regards its possible manners of response/interaction with its surroundings. The properties that a system will manifest, and which will be significant in describing its behaviour, may evolve radically — and (viewed from the outside) unpredictably over time.

(iv) Observable regularities may be defined in two ways: (a) the stability or continued existence of a distinct entity (object, system, organism); and (b) a law or some other sort of identity relation governing the interactions or relationships occurring between systems or components of systems (e.g. conservation principles, constraints on possible interactions). Descriptions in terms of entities (enduring substantial structures), and in terms of parametric regularities (enduring formal identities) are complementary.

(v) All observable regularities are, nonetheless, liable to transgression, breakdown or violation in the course of time.

Let us return, in this light, to the AMORAD problematic of the risk of propagation of radioactive materials and their ingestion by living organisms (humans and also non-human plant and animal species). While radioactive materials do exist in nature, here we are concerned with the products (or by-products) of human ingenuity. The biologically defining property is, in the first instance, the capacity of moving particles (so-called alpha-, beta- and gamma-rays) and of radioactive isotopes close to or absorbed within an organism, to induce disruptions at chemical, metabolic and behavioural levels, sometimes provoking death. To characterise this toxicity, it is nonetheless necessary to consider each pollutant type (at molecular, atomic, isotope and particle levels), in relation to the specific propagation pathways, the types of system that it may enter, and the time-profile of radioactive transformation (or “decay”) and other types of perturbation to the healthy functioning of the living systems.

Changes in macroscopic behaviour, at the level of an organism or a population or an ecosystem, are here induced by virtue of events and activity at microscopic levels. This ramifies into social dimensions, with perceptions that, beyond impacts on individual organisms, entire regions and populations may be at risk and, cumulatively, humankind may be poisoning the planet. Societal responses will contribute to novel technologies and their deployments, in various aspects of governance, including contaminated site remediation, changes in resource use patterns (soils, water, fisheries...), employment and settlement patterns. Processes of *ex ante* foresight and *ex post* adaptation to ever-changing information will continue indefinitely. Deliberate responses to perceived new opportunities and dangers will be interwoven with non-realised expectations, surprises and abandoned plans.

Across all these organisational scales, types and levels, there is a complex interplay between material changes, human perception and evaluation of significance of these changes (past or anticipated), imaginative projection into the future, and real contributions to ongoing changes. The debates, institutional reforms, and conflicts that ensue, are themselves moments in the change process. Efforts to remedy existing damages, or to abort anticipated undesired effects, will contribute to new effects. Activities of research into actual or likely impacts (such as the AMORAD Project), will themselves contribute to changes in system pathways. This is, in part, by design — in a process of “cumulative causation” where, paradoxically, the intent is to induce changes in the perceptions and actions of the stakeholders around the study, but without the exact consequences being known or knowable in advance.

In common with Descartes, our vision of the challenges of risk governance is still based on a demarcation between two distinct “orders” of causality. But, in the framework of complex systems

theory, we now have a much more nuanced vision of their interplay. In **TABLE 1** below, we set out a matrix framework for considering, in pairwise terms, the interplays of the two different classes of causality. In a full anthropological exposition, we might distinguish four categories: (1) Natural law or lawfulness of natural processes; (2) Human agency or volition; (3) Chance or so-called random events; and (4) Super-natural causes, including various notions of original and final causes, and Divine intervention. These four “orders” of causality are, in any given societal context, candidates as explanatory desiderata concerning a phenomenon of interest and, more particularly, its lawfulness and predictability. Views about the respective domains of application, their relative importance, and their interactions, depend on amalgams of beliefs, sentiments, and culture in the broad anthropological sense of the term.¹⁴

If we were to make pairwise combinations of four causality orders, there would be $4 \times 4 = 16$ pairings. However, modern paradigms of risk governance tend to exclude the super-natural as a class of causality. This means that we can pass from 16 to $3 \times 3 = 9$ combinations. Modern science tends also — more paradoxically — to exclude “chance” or randomness as an authentic class of causality.¹⁵ With this further reduction, we pass from 9 to $2 \times 2 = 4$ pairwise combinations, the subset shown in Table 1.

		Subsequent causal element	
		Natural Lawfulness	Human Volition (Choice)
Initial causal element	Natural Lawfulness	EMERGENT COMPLEXITY (deterministic chaos feeding into deterministic chaos)	NATURAL CATASTROPHE (Example: Tsunami and human responses to the Fukushima disaster)
	Human Volition (Choice)	UNINTENDED OUTCOMES (Example: A technology accident at Chernobyl, leading to ecological catastrophe)	SOCIETAL CONTROVERSY (Various manifestations of Societal Conflict and Resolution)

Table 1 — Concatenations of Causalities in application to Nuclear Accidents

Return now to the question of nuclear power plant dysfunction or accident. In a modern vision of universal causality, an “accident” cannot easily be admitted as a truly random or chance event. This is exemplified by the historical cases involving nuclear power plants. There is a spontaneous tendency — after the event — to search for proximate causes. Was the misfortune provoked by inadvertence or human error (3-Mile Island, Chernobyl?); or was it provoked by natural catastrophe (Fukushima?).

In this way, we motivate and illustrate the entries of the two off-diagonal cells in Table 1. The melt-down and explosion of the reactor at Chernobyl was induced by human agency (some mix of faulty maintenance, inadvertence, and error), with subsequent propagation of radioactive materials by natural processes. This corresponds to the lower left cell. By contrast, the dysfunction of the reactors at Fukushima was induced by the sudden irruption of known natural forces (earthquake, tsunami and flooding of the reactors), with subsequent human actions seeking, with urgency, to prevent a major core explosion and to contain, mitigate and clean up the ensuing radioactive contaminations. This corresponds to the upper right cell. In both cases, there is human agency entangled with natural

¹⁴ O’Connor (1993) citing diverse anthropological sources, remarks on the concertation of natural, human and supernatural causalities in order to banish any notion of randomness in a Polynesian “magical” sensibility. In an anthropological perspective, we should not consider these four categories as having any particular hierarchy. Whereas in the modern worldview, there is a (sometimes uncomfortable) coexistence of natural lawfulness and human volition, and a (sometimes ambivalent) tendency towards repudiation of randomness and the supernatural.

¹⁵ As Albert Einstein famously affirmed (without proof), “God does not play dice”. To understand how this elimination of “chance” is (or is not) achieved, we would need not only to address further the status of mathematical probability theory as an explanatory desideratum, but also to look again at the old debates in theology and philosophy between freedom, chance and necessity — now renewed in the dialogues at the interface of science and religion (including, but not limited to, biology, cosmology and quantum physics).

causality. The challenge for a science contribution to risk governance, is to form a clear view of this entanglement of causalities, in relation to past events, and looking forward to the future.

§6. Vulnerability, Dilemmas and the Social Science of Becoming

Across all this, there is the human experience of vulnerability. A dictum of scientific ecology is that everything is connected to everything else. As a corollary, everyone is vulnerable to everyone else. Material examples are viral epidemics, climate change, and toxic chemicals. There are also financial system crashes, Fake News, and sundry other forms of social network contagion. Collectively, we are incessantly and irreversibly negotiating our conditions of survival or success. Moreover, as we push out the frontiers of knowledge, and our corresponding capacities for action, we are confronted with deepening asymmetries in our knowledge set and in our vulnerabilities which, propagated in material and digital terms across the lands, seas and air of our planet, outrun any mastery that we might have imagined of the transformations that we induce.

The complexities of nuclear technology risk governance desiderata arise not so much from the limitations of models and the “gaps” in our knowledge set as, more particularly, from our experiences of identity, of purpose, and of vulnerability. These existential considerations are what, as much as any knowledge base, feed our fears and enthusiasms, impulse our actions and interactions, inform our judgements about these actions and their possible effects, and — through all of this — animate controversies and negotiations.

The human experience of free will is the capacity and indeed the necessity to make choices, to engage in selected courses of action (rather than others). This is not a repudiation of the lawfulness of natural processes. Just as natural lawfulness allows for the emergence of self-organising structures (including living organisms, ecosystems and natural habitats), so this same Nature allows us to experience, and work through, incessant dilemmas of action.¹⁶ The contributions of free will in risk governance are complex.

- ◆ First of all, as beings with consciousness (and a conscience), we act with purposefulness. This purposefulness can be expressed in precaution and preparation, in anticipation of danger (such as a technology accident); and in responses to an accident or other misfortune, after it occurs.
- ◆ Second, there is not one purpose in society, but many. Society is characterised by the clash of many different wills, expressed typically as controversy and conflict. Sometimes there is negotiation and compromise, on other occasions there is violence. In all cases the confrontation of wills is a factor in emergence of new experiences and of new phenomena.
- ◆ Third, in part due to natural complexity but also due to the concatenation of human motives and initiatives, there is the ubiquity not only of projects and purposes, but also of surprises, of accidents, of confrontations and reversals, of unplanned, unexpected and unintended events.

Summing up, if we wish to build science-based representations of accident impacts in a useful and pragmatic way, we need a method of acquisition, synthesis, and restitution of knowledge about past and (hypothetical) future accidents that takes account of the intrinsically incomplete character of our knowledge, while nonetheless positioning it as a societal resource for orienting action. We must identify robust ways for **structuring and making visible the multiple stakeholder perspectives and preoccupations** (i) that are sincere and, where possible, evidence-based, (ii) that are seen as legitimate and credible by stakeholders, and (iii) that do not overly depend on detailed quantitative data and

¹⁶ Human awareness as a contributing factor to the indeterminacy inherent in societal and ecological coevolution is evoked, in the Post-Normal Science context, by Funtowicz, O’Connor & Ravetz (1997) and Funtowicz & O’Connor (1999), coining the term emergent reflexive complexity. In a more philosophical mode, Egginton (2023, p.275) has remarked, in his reflection on the life and writings of Borges, Heisenberg and Kant, that our sense of capacity to act, our freedom, “... is a necessary postulate for a being who can imagine having chosen differently, the condition of the possibility of conceiving of that life as one possible path among many”.

statistics that, very often, are neither available nor readily intelligible. We must assure the mobilisation of knowledge propositions in a way that takes account not only of the diversity (and dispersal) of sources of knowledge, but also the diversity within and across societies of notions of what is at stake — what is important (in terms of identity, wealth and values), why it matters, and to whom?

PART II

The INTEGRAAL Cycle: Structure and Process of Deliberative Evaluation

§7. Participatory Integrated Assessment: The INTEGRAAL Cycle

For an event with ramifications as varied, as far-reaching, and as contingent as a nuclear technology accident, impact assessment raises a host of questions. Do we focus on dispersal of radioactive materials? On the environmental and human health outcomes of uncontrolled radioactive material release? On the opportunities, costs and obligations of possible strategies of post-accident adaptation? Or all of these? With what concepts and conventions do we portray the impacts, as physical changes and for their societal significance? How do we manage the inevitable confrontations, confusions and controversies about uncertainty, and about unreconciled knowledge and value claims? What are we wanting to learn and do through making the evaluations? Is there any prospect of consensus?

There is now a very vast literature on the benefits to be hoped from the concertation of stakeholders in technology assessment, risk governance, and other classes of social choice problems. According to this literature, the fulfilment of hopes for *integrated assessment* would depend not only on an adequate science base, but above all on the embedding of the relevant science in collective learning. This means, on the one hand, the sourcing of knowledge from a range of people and in many different forms, and, on the other hand, a negotiation across a broad spectrum of stakeholders about the quality of different proposals for action. Prospects for socially robust collective choices may be explored through bringing stakeholder perspectives into constructive dialogue with each other, in order to search for a common ground of action in both knowledge and value terms.¹⁷

This is what is meant in the Post-Normal Science literature by mobilisation of the **Extended Peer Community** (Funtowicz & Ravetz 1993; Funtowicz & Strand 2007). Knowledge and learning partnerships are necessarily constructed through active dialogue and co-operation of stakeholders as (i) carriers of knowledge and insights, and (ii) carriers of value propositions about what matters and why. Carriers of knowledge propositions include (but are not limited to) scientists and technical experts; and, equally, scientists and technical experts will bring their own value-judgements as participants in the extended peer community.

From a method point of view, we are in something of a chicken-and-egg situation. This is not in a matter of simple curiosity; on the contrary we want to build up and mobilise knowledge so as to improve societal resilience and capacity in the face of a high-stakes contingency.

¹⁷ Some useful entrées to the deliberative evaluation literature as it has developed since the 1990s are provided by Simos (1990); Dryzek (1994), Holland (1997); Jacobs (1997); Bulkeley & Mol (2003); De Marchi et alii (2000); Dryzek & List (2004); Procter & Drechsler (2006); O'Neill (2007). Reviews of arguments for extended stakeholder involvement in technology and policy assessment are found in Faucheux & Hue (2000, 2001), Faucheux & O'Connor (2000), O'Riordan T. & S. Stoll-Kleeman (2002), and Frame & O'Connor (2010). Overviews of the process and outcome quality motivations for integrative assessment, are provided by Van den Hove (2000, 2001) and O'Connor & Van den Hove (2001).

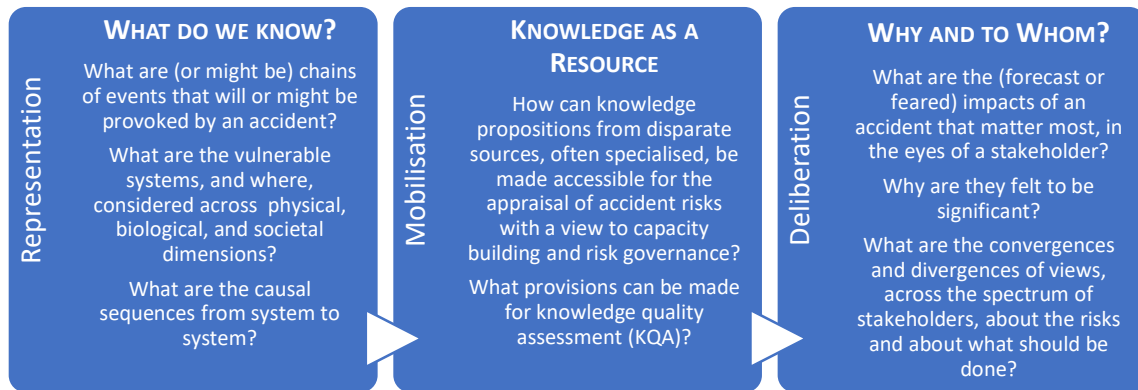


Figure 1: Representation, Mobilisation and Deliberation as facets of Impact Assessment

Should we focus on the science base, and proceed to explore the lessons for society, as indicated by the direction of the arrows in **Figure 1**? Or should we, on the contrary, start from a scoping of society’s main fears and preoccupations, and then work backwards to ask how can we mobilise science to provide a strengthened knowledge base about these preoccupations?

In our view, the answer is to work in both directions, simultaneously. In other words, we must work at the cross-roads of knowledge and values. We must find a way to situate scientific (and other) propositions of knowledge in their societal context, parsimoniously, while respecting simultaneously their status as knowledge claims, and their status as signals about something that matters in society.

To this end, we address accident impact assessment by asking, simultaneously, (1) **what are (or might be) the changes** being provoked in the affected systems considered in their various physical, biological, and societal dimensions; (2) **to whom** are these changes significant; and (3) **for what reasons** are these impacts (or feared impacts) felt to be significant?

We choose, for this purpose, to adopt a framework for participatory integrated assessment known as the *INTEGRAAL* Cycle,¹⁸ proposing **deliberative multi-criteria multi-stakeholder evaluation** as a framework for the *ex ante* assessment of the possible impacts of a nuclear accident. The application of this six-step schema to our AMORAD problem, is set out in **Table 3**. Subsequent sections present details of the KerBabel deliberation support tools (**sections §8 and §9**), the conventions that we have adopted for the structures or frames of our AMORAD *ex ante* and *ex post* evaluations (**section §10**), and the variety of sources that have been and might be exploited for a representative diversity of knowledge propositions (**section §11**).

¹⁸ This schema has roots in the VALSE Project vision of environmental valuation and sustainability assessment as a collective social process where formal tools are embedded in wider contexts for negotiating meaning and purpose (O’Connor 2000) and draws on experience since the 1990s with participatory integrated environmental assessment (see Frame & O’Connor 2011 for a synthetic overview. O’Connor (2002) had employed the term “Theatre of Sustainability” for an analogous vision of a cyclic iterative participatory process. O’Connor & Spangenberg (2008) set out detailed steps for participatory indicator-based approaches to CSR reporting as an exercise in multi-stakeholder multi-criteria evaluation. Expositions of the *INTEGRAAL* procedure for territorial applications are found in numerous French language publications and reports including Chamaret, Reichel & O’Connor (2009); Reichel, Chamaret & O’Connor (2010). The name evokes an integrative process seeking the virtuous but utopian (Holy Grail) status of reconciliation — that is, consensus solutions to “impossible” social choice problems.

Table 3 — The INTEGRAAL Cycle for AMORAD Evaluation Exercises

INTEGRAAL	Generic Description of the Step	KerBabel Conventions for AMORAD
Step ONE. What's Our Problem?	Identification by the stakeholder community of “ <i>our common problem</i> ”. This step may engage stakeholder consultation and deliberation; and it delivers the context, the scale, and the dynamics of the formal deliberation process to come.	We want to provide a method for <i>ex ante</i> appraisal of the possible impacts of a future nuclear accident, drawing on (a) insights from <i>ex post</i> evaluations of past events such as Chernobyl and Fukushima, (b) scientific knowledge of causal pathways of health and environmental impacts, and (c) stakeholder views on the significance of possible and likely impacts.
Step TWO Structure the Evaluation Tasks	Organise “our common problem” in terms of the categories of actors concerned, the objects or options being assessed, and the value criteria. This means developing typologies for (1) the spectrum of stakeholders; (2) the projects, policies, strategy options, and scenarios to be appraised; and (3) the principles of performance, quality and acceptability that the stakeholders hold.	The KerBabel Deliberation Matrix with its associated KerBabel Representation Rack (KRR), is deployed to provide a framework for “scoping” the vast spectrum of possible environmental and societal impacts, and for the signalling by stakeholders of the significance of the different impacts (that is, of “what is at stake”, in their eyes, in the identification of the “risk” itself and in the event that an accident occurs).
Step THREE Prepare Knowledge Resources	Identify and mobilise tools for system representation (e.g., maps, data sets, models of processes and systems) that can help to ground the deliberations in a robust knowledge base and that will assist in preparing catalogues of indicators representing the stakeholders’ reference points when working to evaluate situations and scenarios.	The system needing to be represented in AMORAD is vast, composite and multidimensional, being human societies and their biophysical environments from sub-atomic particle to continental and ocean scales. We exploit knowledge mediation tools in the ‘ePLANETe’ platform (notably the KIK, <i>Heritage Parks</i> , <i>Virtual Biodiversity Garden</i> , & <i>Territorial Food-basket galleries</i>) for portrayal of a <u>representative diversity</u> of objects at multiple scales, from the point of view of their significance, inter-connexions, and vulnerabilities.
Step FOUR Exercises of Deliberative Evaluation	Mobilise actors for tasks of deliberation. This step depends on the frameworks and information developed in Steps 1-3 above. Using functionalities of the KerDST Deliberation Matrix on-line, it produces outcomes in the formal sense of multi-actor multi-criteria evaluations. Simultaneously it provides insights and learning opportunities to participants.	The Deliberation Matrix provides for the declaration by (or on behalf of) <u>each</u> category of stakeholders, of <u>judgements</u> about <u>each</u> component of the environment or society, relative to <u>each</u> risk governance issue. A composite picture is built up, through mobilisation, cell-by-cell, of indicators or arguments that are carriers of simultaneously descriptive and normative information. The indicators are <u>knowledge propositions</u> documented with meta-information profiles in ePLANETe galleries.
Step FIVE Restitution of Results	Communication of Results & Recommendations. This includes, but is not limited to, the reporting of outcomes of an evaluation exercise. It also includes all tasks “along the way” of information sharing relating to the design and preparations of deliberations, documentation of discussions and intermediate results.	Our work provides a frame for the “scoping” of the spectrum of likely or possible impacts on society of a major nuclear technology accident. It also provides a frame for reflexion about the ambitions and roles for science contributions to risk governance.
Step SIX Start all over Again	Reflection on the outcomes obtained and, in an iterative sense, a return to Step ONE of the process, in order to review the entire evaluation sequence or, as seems fit, to repeat the exercise or formulate new specific evaluation problems.	The <i>ex ante</i> analyses are intended to inform actions with multiple time-frames: prevention of a future accident, mitigation of its effects, preparedness in the event of misfortune (including prepare the terrain for <i>ex post</i> evaluations, if and when pertinent).

Source: the authors. Although presented here as a sequence of steps, *INTEGRAAL* is not a linear process. The idea is to constitute a forum that offers an ongoing opportunity to participants to explore progressively, or in parallel, different aspects of the “stakes” of nuclear technology risk governance.

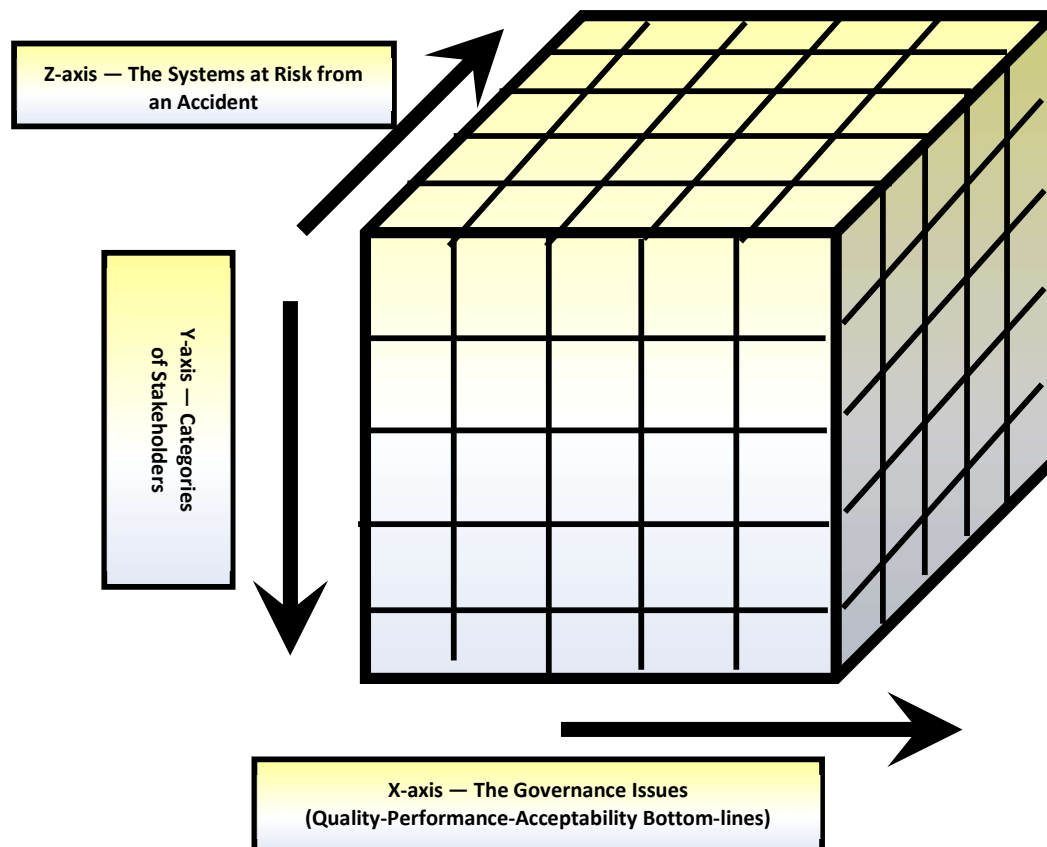
§8. The Structure and Purpose of Deliberative Evaluation

The word *évaluation* has many connotations, including that of quantitative measurement. For our AMORAD purposes, we consider evaluation methods — from *ex ante* risk appraisal to *ex post* social acceptability of post-accident adaptation strategies — as the comparison of one thing or action with another, in qualitative or quantitative terms. A typical evaluation perspective, in this regard, is to compare and contrast different opportunities for action. We can also compare objects for their relative qualities, in order to better understand them, without yet specifying an action.

In AMORAD, our task is to characterise the likely or possible effects of a nuclear technology accident, from the point of view of their significance in the eyes of different members of society. We employ a tool for comparative evaluation, referred to as the **KerBabel Deliberation Matrix** (or KerDST, for short) whose logic is to express a generic *problem of social choice* (cf. Arrow 1963; Dryzek & List 2004; O'Connor 2002) within an operational framework of multi-stakeholder multi-criteria deliberation support. The evaluation problem is structured along three dimensions (see **Figure 2**), the axes of the Deliberation Matrix. These portray:

- (1) The **OBJECTS** of comparative evaluation attention (which can be, depending on the problem, scenarios, alternative sites, investment strategies, public policy options, and so on).
- (2) The spectrum of the **PERFORMANCE GOALS AND CHALLENGES**.
- (3) The different **ACTORS OR STAKEHOLDERS** involved in, or potentially affected by the problem.

Figure 2: The Structure of the KerBabel Deliberation Matrix for AMORAD
(Source: the authors).



The KerDST tool invites the declaration by (or on behalf of) *each* category of stakeholders, of **judgements** about *each* of the objects, options or scenarios under evaluation, with reference to each consideration in the *spectrum* of governance or quality-performance issues. There are several different mechanisms available for this process, which we outline progressively in the sections that follow. Most often, we envisage the mobilisation of indicators or arguments as carriers, simultaneously, of descriptive and normative information (see **section §9** below). In the context of AMORAD, we use the terminology **knowledge propositions**, even while insisting on the heterogeneous and often unproven status of these propositions (cf., Douguet, Lancelleur & O’Connor, 2024).

What is the ambition of such a tool? The years 1990-2010 were characterised by a plethora of experimentations with evaluation frameworks making explicit the plurality of values (implying multiple evaluation criteria) and the plurality of classes or components of society (implying the pertinence of multi-stakeholder and deliberative perspectives). In its ambition at that time, the **KerBabel Deliberation Matrix** could be seen as an innovation at the interface of experimentation with (1) the new digital technologies for “web services”, and (2) the preoccupations for stakeholder participation in action-research programmes of integrated environmental assessment.¹⁹

O’Connor & Douguet (2024) have reviewed some of the formulations since the 1990s of “matrixial” approaches to knowledge-values-action problems. Quite a few suggestions have been made for applications to nuclear technology and waste management problems (for example: Oughton et al., 2004; O’Connor 2009; Faucheux & O’Connor 2005, 2015; Cotton 2009). Matthew Cotton (2009) sets out a sketch of an “Ethical matrix” (as proposed by Mepham 1996, 1999) for assessing the quality of radio-active waste management siting strategies relative to different normative principles or precepts. He insists on the paradoxical ambition of matrixial approaches, as a sort of meta-method sitting on the cusp between normative and descriptive considerations.

“The [ethical] matrix is intended as a tool for mapping out the issues underpinning a decision, rather than determining an ethical decision using some supposed metric of evaluation. By refraining from rule making or adhering to ethical doctrine, Mepham argues it is ethically neutral in its intent (Mepham 2000). Such neutrality is a requirement for pluralistic deliberation on ethical norms, moral values and their application to RWM policy. The matrix therefore alludes to Habermasian discourse or procedural ethics, whereby the argumentation of moral principles by (communicatively rational) individuals ascribes ethical value to a decision (Habermas 1980; Johnson 1991). By considering a range of normative principles, the matrix seeks to remove philosophical bias in influencing the decision outcome.”

The term “ethically neutral,” is perhaps unsatisfactory; a more adequate formulation would be in terms of “reflexivity”. What is sought is not so much to “remove philosophical bias in influencing the decision outcome,” as to make visible, or *render explicit*, the value judgements, the normative, cultural and philosophical premises that inform and motivate a judgement — that push (as Rittel would say) “for and against” different judgements about the severity of an impact, for or against different propositions of action, and so on. Another useful formulation in this regard is provided by Samuel Camenzind (2023) who, in discussion of ethical positions around controversial topics, insists that the ambition in the first instance is for tools that help to describe situations of controversy, not to resolve normatively the controversy:

“The only known fact about the members M of the moral community C is that every action A that involves a moral relevant being B must be justified with morally relevant reasons R ...”

¹⁹ The neologism DST (for **DELIBERATION SUPPORT TOOL**) is used here in differentiation away from the more established DSS (decision support system), making clear that the accent here is on **deliberation support** and not simply ‘decision’. This dates from the first prototype multi-media implementation of the **KerBabel Deliberation Matrix** concept, during 2001-2002 in the context of the EC-funded multi-partner **GOUVERNe** project on interactive tools for integrated management of ground water resources (see O’Connor 2006; Amorsi 2013). Some key points and further references are given in **APPENDIX ‘B’**.

In the KerBabel perspective, the ambition is similarly descriptive. Through the interfacing of typologies along each of the WHAT, WHO and WHY axis, the KerDST framework establishes a “crossroads” between descriptive and normative dimensions of evaluation — that is, between knowledge and values. The intention is to propose, along each of the 3 axes, a “representative diversity” — that is, parsimonious typologies within which all stakeholders and arguments can “find” themselves, while expressing the diversity of their preoccupations.²⁰ This ensures the visibility of each stakeholder class as contributing members of a collaborative deliberation process — corresponding in the language of Post-Normal Science to the Extended Peer Community. It makes possible the portrayal of convergences and divergences between stakeholders along both knowledge and value planes.

The purpose of this sort of deliberation framework is, thus, not to amass data in a simple decision support goal, but to build up a composite picture of what matters to people and why, as a resource for ongoing negotiation and collaborative learning. The goal is not to resolve a controversy (except in the sense of “see more clearly”), but to provide a **structured representation of the unresolved controversy**.

So, we are not seeking to provide a definitive view of the impacts of a nuclear accident, either in descriptive or normative terms. We are aiming at “clumsy solutions” (Verweij, et al., 2006), through parsimonious portrayal of **the spectrum** of predictions and preoccupations across science and society.

§9. Conventions for the Cataloguing of Knowledge Propositions

The **KerBabel Deliberation Matrix** permits a didactic presentation of the process and outcomes of **judgements** offered by each category of stakeholders, for each of the objects under evaluation, with reference to a spectrum of governance or quality-performance issues. The principle is that that each stakeholder class should offer a judgement (e.g., *satisfactory*, *poor*, *intolerable*, etc.) of each option/scenario in relation to each of the key governance or decision issues.

One obtains in this way, for each stakeholder (or actor class), a rectangular array of cells, each array being a layer of the Matrix, within which each row represents (issue by issue) the evaluations furnished by the given class of stakeholders for successive options/scenarios. Or, looked at from another angle, one obtains the evaluations by each stakeholder, of a given option/scenario.

In more technical terms, the method of the KerBabel Deliberation Matrix is for **SIGNALS** to be placed in a cell, or “basket”, where they are attributed a **qualitative value** (typically with a colour code, such as “Green-Yellow-Red” or any other sequence according to need) and a **weighting** relative to other Signals in the same basket.

Several tool variants are available for the composition of an evaluation exercise. The simplest procedure, which can be carried out on paper or on-line, is that of “Colouring in the Cells” by single representatives of each stakeholder category (or by a single expert acting “on behalf” of all stakeholder categories) for a qualitative multi-stakeholder multi-criteria assessment of a situation or of options for action. This simple procedure can then be enriched,

- On the one hand, with variations where several participants within each stakeholder category contribute to a “composite” judgement per issue (that is, per cell); and,
- On the other hand, towards mechanisms for “deepening” the knowledge resources, where representatives of each stakeholder category (or experts acting “on behalf” of all stakeholder categories) work to produce an evaluation supported by indicators, thus linking indicators to each of the societal performance-quality issues.

²⁰ The frame adopted at any time can, in principle, be modified by iteration as a pragmatic expression of stakeholder, academic, knowledge quality, and communication concerns.

In the case of an indicator-supported evaluation, it is necessary to compile a **'BASKET' OF INDICATORS** that, in the eyes of the stakeholder, signal key attributes of the object (scenario/choice or activity/site/territory) under scrutiny, relative to the performance issue. The judgement at the cell level in the Matrix is obtained not by a simple choice of colour for the cell, but as a weighted “amalgam” of the qualitative judgements assigned to each indicator in the “basket”. Each cell therefore carries a **“composite” signal**.

The **SIGNALS** to be contributed into Deliberation Matrix cells can thus take many different forms, passing through a continuum from the most primitive (as a simple opinion 'Good' and 'Bad'), to the more sophisticated forms. In the AMORAD context, we have made a distinction between:

- Discursive **Arguments** or **Justifications** expressing the judgement being conveyed about the situation (in our case, a feared or forecast impact of an accident); and then, as a further dimension, the opportunity for this Argument to be supported by reference to auxiliary references (e.g., with hyperlinks to any sort of contents on websites). and
- Various classes of **Attributes of the Object/situation** that, with the *weights and value judgements attributed by the participant*, are given the status of **Indicators** relative to a specified Quality concern.²¹

There is a continuum between 'Arguments' and 'Indicators'.²² We employ the generic term **SIGNAL**, understood in a broad sense, as any pertinent feature, qualitative or quantitative, of the situation or scenario being analysed. Data, documents, images, or any other knowledge proposition considered by a participant in the deliberation to constitute evidence, may be mobilised as a Signal.

From a method point of view, what is important is this declarative process, is the triangulation that situates each of the knowledge-value propositions brought to bear as an indicators or argument in the evaluation, simultaneously relative to one or more stakeholders (WHO?), one or more considerations of action (WHAT?), and one or more fields of normative preoccupation (WHY?). The mobilisation of signals by a given Stakeholder class, for a given performance Issue, applied to a given Site or Option for action, constitutes a declaration de facto of the **pertinence** — or **fitness for purpose** — of the knowledge-value proposition as a signal about the Quality of the different objects or options for action.

The population of **Signals** — that is, the candidate knowledge propositions, whether considered as Indicators and Arguments — can be augmented freely in the course of a deliberation exercise. In the KerBabel methodology, all such signals, considered as knowledge propositions available as resources to be mobilised in deliberation, are managed by on-line meta-data systems — referred to as galleries — whose role is to pre-classify Signals in terms of their contextual 'Fitness for Purpose' for informing deliberations. These galleries are, in their turn, managed within the 'ePLANETe' platform (see Lancelleur 2019). We will not present all the galleries of ePLANETe, as there are more than twenty.²³ In a parsimonious way, **Figure 3**, we highlight their differentiation on methodological terms. We distinguish between:

²¹ The mobilisation of **monetary signals** of costs, risks and benefits associated with different facets of the problem being addressed, can be considered as a distinctive sub-set of such Indicators. Monetary values can be indices of the significance of an impact (see Ramirez 2002 and Appendix F for an example in the AMORAD context), and they can thus also play an important role in the evaluation of options for action in both *ex-ante* prevention and *ex-post* adaptation contexts. But, without any exclusivity in our multi-criteria framing.

²² One might be tempted to reserve use of the term 'Indicator' for an attribute of the situation whose factual character (observability) is the object of a broad consensus across stakeholders (though the meanings or significance attached to this attribute may diverge widely between different stakeholders). 'Arguments', by contrast, whether or not having a measurable component, may have deeply subjective or metaphysical dimensions, while still being admitted as pertinent deliberation desiderata.

²³ A complete presentation of the galleries of ePLANETe, with their philosophical background in emergent reflexive complexity and an indication of their pertinence in deliberative risk governance such as AMORAD, is found in the research report by O'Connor, Lancelleur & Douguet (2024).

- **Tools for conducting an evaluation exercise**, notably the Deliberation Matrix itself, providing a framework for the signalling of knowledge propositions on the interfaces of what, who and why.
- **Tools for the pre-classification of knowledge propositions** (Indicators and Arguments) in anticipation of their exploitation as signals to inform an evaluation. These include notably the KerBabel Indicator Kiosk (KIK) and the KerBabel Representation Rack (KRR).
- **Tools for the representation of key features of the objects of evaluation attention**. As a function of the analysis situation, these “objects” can be scenarios, options for action, technology or investment alternatives, sites or systems. Examples of such galleries relevant to AMORAD are the “Heritage Parks” gallery, the “Virtual Biodiversity Gardens”, and the “Territorial Food Baskets”, all of which will be described very briefly in **Section §11** below.

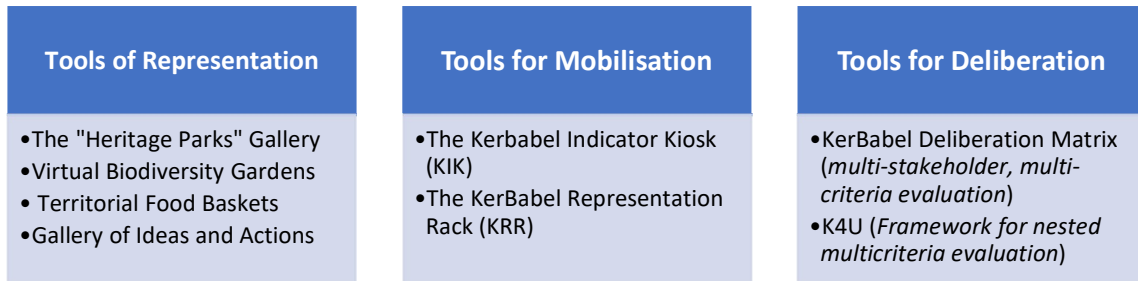


Figure 3: Methodological Classification of Galleries in ‘ePLANETe’

Source: the authors.

The KIK and the KRR as tools for classification of categories or items of information as knowledge propositions, occupy a service role of intermediation between “raw” sources of knowledge propositions in society (such as scientific publications, models, maps, and any other sort of symbolic or discursive material) and the strait-jacket framework of the KerBabel Deliberation Matrix.

The **KerBabel Indicator Kiosk** (KIK for short) is a meta-information cataloguing tool, composed and managed since 2004 by a Content Management System (successive versions of the CMS Drupal), now a relational data base integrated within the vaster ‘ePLANETe’ platform. The key KIK functionality for building a deliberative evaluation exercise, is to provide a comprehensive profiling of an Indicator concept as a knowledge proposition available to be declared as a signal in a cell of the Deliberation Matrix. The emphasis being on ease in the definition and mobilization of a system attribute deemed of descriptive and normative pertinence, only a very limited number of meta-information fields are obligatory for the creation of an “Indicator” profile in a KIK. Optional fields can provide deeper characterization, including sources and uses of empirical data in pre-existing applications.²⁴

The **KerBabel Representation Rack** (or KRR for short) characterises the Pertinence of an Indicator concept by an index situated at an intersection point of four axes of classification. Whereas the KIK tool offers a “generic” framework for the cataloguing of signals, the KRR provides a circumstantial classification that relates directly to the evaluation problem at hand. In economics language, we can say that the KRR classification axes relate to the contexts of production (or offer) of knowledge propositions, and of use of (or societal demand for) the knowledge propositions.

²⁴ KerDST users are in fact invited to propose the inclusion of **indicator concepts** as “Signals” within each Deliberation Matrix cell or “basket”. In operational terms, they are invited to make a selection from the collections of digital objects — presented with succinct meta-information profiles (the object’s Identity Card, as it were) — in the galleries in ePLANETe that are available as satellites relative to the Deliberation Matrix itself. This means, importantly, that the KerDST user is not required immediately to search for data corresponding to an indicator, nor to verify/validate others’ data. The contribution at the cell level the KerDST evaluation process is situated at the concept level, that is, mobilising a signal described principally with **meta-data**.

In the frame of the Deliberation Matrix, we can think of the stakeholders as the users (or consumers) of knowledge propositions, exploiting them to make declarative judgements about what matters (and why) for each object under scrutiny. The KRR classification system incorporates, for the characterisation of the contexts of Use or “Social Demand”:

- The typology of **OBJECTS** to be Compared.
- The typology of **QUALITY/PERFORMANCE ISSUES** identified as relevant for the evaluation exercise.

This means that the KRR structure incorporates two of the three axes defining a Deliberation Matrix; but it does not incorporate the axis of Stakeholders in the deliberation.²⁵

Pushing further the idea of a knowledge marketplace, we can enlarge our considerations of pertinence to the “production side”. On the Production or Social Supply side, the KRR axes relate to:

- The different classes of **KNOWLEDGE CARRIERS** (for example, different domains of scientific analysis, but also different domains of societal expertise, wisdom, and opinion).
- The spectrum of **CONCEPTUAL FRAMES** which are sourced or mobilised by the Knowledge Carriers, and which thus characterise the production of knowledge propositions.

Reasoning from the Production or Supply side, one can imagine that a knowledge proposition (e.g., data set, model variable, or other information category or concept) is put forward by a specific class of **KNOWLEDGE CARRIER**, grounded in a specific **CONCEPTUAL FRAME**, and suggested as pertinent for the comparison of Objects relative to this or that Performance/Quality Issue.

Reasoning from the User or Social Demand side, one can imagine that a knowledge proposition (e.g., data set, model variable, or other information category or concept) is retained, in anticipation of a deliberative evaluation exercise, as pertinent for the comparison of **OBJECTS** relative to this or that **PERFORMANCE/QUALITY** Issue, and that this leads back to the specification of the origins of this knowledge proposition by its localisation with a specific class of Knowledge Carrier and grounded in a specific Conceptual Frame.

Summing up, we have five structuring axes, two of which are present in both the KRR for Signal classification and the Deliberation Matrix, two of which are only in the KRR, and one of which relates uniquely to the Deliberation Matrix. In order to build a deliberation problem, we need to specify the categories along each of these 5 axes. WHAT should we set out to evaluate? What are the **Objects to compare**? What are the different **Conceptual Frames** from which Indicators and Arguments are drawn? What are the relevant **Quality considerations** [the WHY? dimension]? WHO is, or should be engaged in the evaluation exercises, either as contributors of knowledge propositions, or as stakeholders expressing a judgement about values and risks? In other words, how should we set out the two complementary typologies of Actors making up the Extended Peer community, considered on the one hand as users of knowledge propositions [that is, as **Stakeholders** participating in the deliberation exercise], and, on the other hand, as producers of knowledge propositions [that is, as **Knowledge Carriers**]?

§10. The AMORAD frames for ex ante Evaluations

In this section we set out the conventions retained for each axis of comparative evaluation, for each class of *ex ante* evaluation. These are our designs for AMORAD operational deliberation support tools.

²⁵ This leaves it open that the classification adopted for the **KNOWLEDGE CARRIERS** (on the production side) may differ from the classification adopted along the multi-actor axis for the **STAKEHOLDERS** (on the user side) in a deliberation exercise. Of course, these two classifications will often overlap (and for particular situations might even be proposed as identical); but, the method allows us to express, in complementary ways, the two faces of the **Extended Peer Community** as “producers” and “users” of knowledge propositions.

We recognise two broad facets, or phases of evaluation for a risk governance situation. The first phase is the characterisation *ex ante* of the situation of risk. The second phase is *ex post* evaluation of an accident (its severity, its effects, its impacts, its significance) and of possible response strategies. These two phases are not completely disjoint. *Ex ante* appraisals of risks of a future accident, look at the past and present, and seek, on the basis of multiple causalities, to extrapolate into the (hypothetical) future. They will, as in the AMORAD Project, draw on and deepen insights from *ex post* evaluations of past events (such as the Chernobyl and Fukushima disasters), identifying the causal pathways of health and environmental impacts, and the efficacy (or not) of post-accident responses.

For the AMORAD project, we developed two complementary frameworks for the investigation *ex ante* of possible effects of a nuclear accident. These are referred to as ‘Matrix A’ (**FORESIGHT**) and ‘Matrix B’ (**FOREBODING**).²⁶ In application of the KerBabel method, we set out below the axes employed for the structure of the evaluation and for the classification of knowledge resources — the candidate Indicators and Arguments — that might be mobilised to build up the “profile” of a possible accident. Then we provide lists of the categories deployed along each of these axes. This paves the way for a short discussion of sources and examples of knowledge resources (**section §5**).

Matrix ‘A’ — Ex ante Impact Assessment [FORESIGHT]

The first framework, referred to as ‘Matrix A’, aims at facilitating the inventory of possible effects through the interfacing of systems science and social significance classifications. It is a framework for science (and social-science) based FORESIGHT. The axes employed are as follows:

- THE POINTS OF VIEW: Sectors of Socio-economic Activity [the evaluation protagonists or stakeholders]**
- THE ISSUES: Dimensions of Vulnerability and Capacity**
- THE OBJECTS OF EVALUATION ATTENTION: Compartments of the Biosphere**
- The Contexts of Knowledge: Historical and Potential Accident Sites*
- The Categories of Knowledge Carriers: Domains of Science and Humanities*

The first three of these axes (**SIGNALLED IN BOLD**) are mobilised directly by the Deliberation Matrix. They frame the evaluation exercise. The triangulation of these three axes means that, in effect, we are considering the “impacts” of an accident not only in terms of the modification of environmental conditions but, more particularly, in terms of the significance of these modifications in the eyes of a Socio-economic sector — that is, in terms of the vulnerabilities and capacities of the actors in each socio-economic sector.

The two remaining axes — the spectrum of historical and potential accident sites; the broad domains of human understanding, *signalled in italics* — are used to characterise the sourcing or production of the knowledge propositions. These typologies are employed in the KerBabel Representation Rack, but not in the Deliberation Matrix itself.

With the ‘Matrix A’ framework, we do not place the focus on accident “sites” as our direct objects of evaluation attention. On the contrary, we consider the sites, along with the spectrum of sciences and humanities, as well-springs of knowledge propositions. The intention of the ‘Matrix A’ foresight

²⁶ From a methodological standpoint, *ex-ante* analyses prepare the terrain for *ex-post* evaluations, if and when such actions become pertinent. So, it can be anticipated that these two frames might be deployed, as an opening gambit, to structure an *ex-post* scoping analysis of (a) an accident crisis as it unfolds, and (b) the spectrum of short, medium and possible long-term impacts of the accident. In effect, a judgement has to be made, for the specific accident unfolding, whether or not a given type of impact is occurring (or is likely to occur) and, if so, what might be its severity. For appraisal of the pertinence, priority, and social acceptability of response actions, somewhat different frames would be required. This is envisaged in our work, but goes beyond the scope of the present contribution.

exercise is to engage the participants in a structured way as contributors to a composite vision of the “potential impact space”. In more detail, the categories along each axis are:

THE CATEGORIES OF KNOWLEDGE CARRIERS — KNOWLEDGE PRODUCTION DOMAINS:

- *The so-called “Hard” Sciences* (Physics & Chemistry), notably of atoms and radioactivity;
- *Sciences of the Physical Environment* (Geology, Geomorphology, Sedimentology, Hydrology, Oceanography, Meteorology, Climatology);
- *Life Sciences* (Biochemistry, Biology, Ecology, Physical Geography);
- *Health Sciences* (Medicine, Radiology, Toxicology, Epidemiology...);
- *Decision Sciences and Governance* (Economics & Management, Law, Legal studies and Political science);
- *Social Sciences, Arts & Humanities* (including Sociology & Anthropology ; Human Geography, Psychology, Languages and Literatures, Fine Arts...)

CASE STUDIES — THE VARIOUS HISTORICAL AND POTENTIAL ACCIDENT SITES:

- *The major historical accident sites:* Three Mile Island, Chernobyl, Fukushima.
- *The big river mouths in France:* La Manche (English Channel); Le Golfe de Gascogne; Le Golfe du Lion.
- The Nuclear Installation Risk Zones addressed by the IRSN (*Fiches Marines* for Toulon, Cotentin, Brest).
- The French CIGEO site for deep underground disposal of radioactive wastes (Meuse/Haute Marne).

THE COMPARTMENTS OF THE BIOSPHERE — THE ‘OBJECTS’ OF EVALUATION ATTENTION

The spectrum of Knowledge Carriers, as set out above, highlights the diversity of scales of physical structures and processes (from atoms to oceans) and of societal organisation (from individuals with their portable telephones, to institutions for multi-national coordination). Nonetheless, the importance of the biophysical environment to human societies can, for many purposes, be considered in a synthetic systemic way, in terms of environmental and ecosystem services. These “services” are divided into four broad classes: the inflows of natural resources (including energy) to society; the outflows of waste materials and energy to the environment; the biophysical environment as an object of sensory appreciation (across the 5 senses); and the physical world as a life-support system.

For our purposes, an adequate portrayal of the spectrum of ecosystem and environmental services is obtained by the exploitation in complementary ways of the frameworks (i) of natural heritage accounting (in French, *les comptes du patrimoine naturel* (INSEE 1986), (ii) of ecosystem accounting as developed in the international environmental and economic statistics community (SEEA 2021, and complementary documents at <https://seea.un.org/ecosystem-accounting>), and (iii) of the UNESCO programme for recognition of natural, cultural and “hybrid” categories of heritage of outstanding or universal value (see: <https://whc.unesco.org/>).

The vulnerability of environmental services to perturbation by human activities, can then be portrayed with the DPSIR framework (Maxim, Spangenberg & O’Connor 2009), where human activities (including nuclear accidents) are the Driving forces (D) provoking Pressures (P) which induce changes in the State (S) of the biophysical environment, whose effects in terms of modified services are felt as Impacts (I) on human societies, leading (after the fact or by anticipation to diverse Responses (R) in a process of cumulative causation.

For a given territory envisaged as vulnerable to a nuclear accident, we can therefore seek to make an inventory of the different services across these four broad categories or, more exactly, an inventory of the significant **changes to these services** that might be provoked by the accident: their disappearance or diminution in quality or quantity. We must also consider in what ways human society might respond to observed or feared changes, as this will have a bearing on judgements about impact significance. In what ways can exposure to fluxes of contaminated materials be controlled or reduced? Can ingestion or other uptake of radioactive materials by microbes, plants, and animals (including humans) be avoided? Can or should the human (and animal) populations of a zone be evacuated? Should the

exploitation of water, and of biological resources (for food and for other uses) be curtailed? What rehabilitation programmes (for buildings, soil, water and living populations) might be envisaged? Over what time spans? And so on.

In order to identify the significant environmental services (or the loss of them), we need to specify their location and their source. This means the attribution of a service to a specific sector or compartment of the biophysical environment. A high-level typology of the compartments of the environment is set out in Table 4. Seven broad categories of “environmental assets” are specified, in line with the international conventions of environmental accounting. For each compartment, there is a corresponding class of biodiversity (shown in the right-hand column). This provides for a specific focus on living organisms, relative to their host media.²⁷

GEO-SPHERE	ENVIRONMENTAL ASSETS BY ‘SECTOR’	BIODIVERSITY
LITHOSPHERE	Productive Soil Assets (Soil Types, Quality, etc)	Land-based (terrestrial) ecosystems
	Underground/Sub-Soil assets [including minerals, energy resources in stock forms, etc.]	<i>(Sub-soil Terrestrial biodiversity)</i>
HYDROSPHERE	Fresh Water [including surface water and major ground-water bodies]	Freshwater ecosystems
	Coastal Wetlands and “transition” zones	Coastal “transition” ecosystems
	Marine water resources	Marine ecosystems (including sea-floor sediment)
ATMOSPHERE	The atmosphere as a Climate system	<i>(Airborne biodiversity at a climate scale)</i>
	Habitat air quality (from the points of view of human health and wider life)	Airborne biodiversity

Table 4: The “Objects” of Accident Impact Assessment
Source: O’Connor & Schoer (2010)

Through this typology, we focus the assessment of the impacts of an accident on the “funds” that constitute the biophysical environment. This opens the way to the representation and evaluation of components of the Biosphere in a patrimonial perspective, that is, as elements of value deserving to be preserved for posterity. (We will return to this perspective in **Section §5**.)

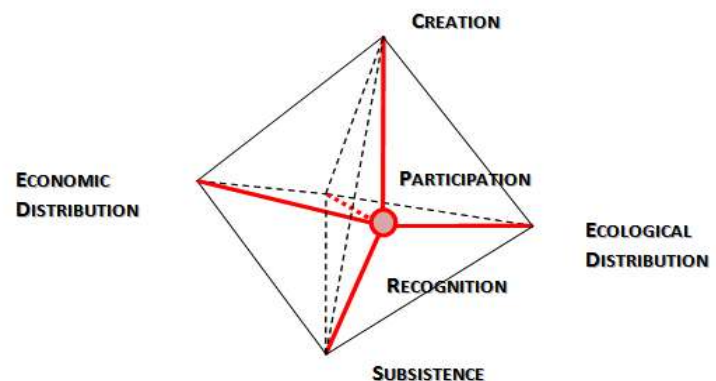
VULNERABILITIES & CAPACITIES (OR, WHY AN ACCIDENT MATTERS) — THE ‘ISSUES’ OR ‘STAKES’

In the assessment of accident impacts, we are not simply trying to identify the changes in environmental and societal systems that have been or might be provoked by the event. We are asking the much more complex question, what changes matter to people, and why? We must reason in terms of perceptions of well-being, opportunity, prosperity, and their negations: loss, danger, misery, deprivation (cf., Faucheux & O’Connor 2017). We structure this dimension, in a very synthetic way, through considerations of wealth and vulnerability, poverty and capabilities as developed in the development literature since the 1970s, for example in the work of Amartya Sen (2009) and Manfred Max-Neef (1991). Douguet et alii (2017) have drawn on these sources to propose six broad categories of vulnerability for assessing the significance of a project or policy — or, in our case, an accident impact. These are:

²⁷ With regard to biodiversity, one might envisage sub-divisions not just relative to the different host milieu (air, ocean, freshwater, land, etc.), but also for distinguishing ‘domesticated’ and ‘wild’ nature, or for separating ‘cultivated’ biological resources and ‘non-cultivated’ biodiversity. It is a matter of analysis purpose and parsimony. In our KerBabel ‘Matrix A’ framework, “cultivated” or “husbanded” biological resources will at any rate be considered simultaneously from the standpoint of an economic sector of activity (see the typology of economic sectors of activity, just below) and from the standpoint of the Biosphere compartment that hosts them.

- ❑ **SUBSISTENCE & SURVIVAL:** The basic health requirements of access to water and food, comfort, shelter, and security. These are biological needs of every person, resolved within society, and pre-conditions for participation in society.
- ❑ **ENVIRONMENTAL DISTRIBUTION:** The conditions of access, individual and collective, to the different sorts of environmental services (life-support; energy and material resources; waste disposal, cognitive enrichment, symbolic value and amenity).
- ❑ **THE SOCIAL DIMENSION:** Recognition, status, belonging – the many different facets of participation as a member of a society, through different forms of community and collective identity (from language and religion to sports clubs...).
- ❑ **FINANCIAL CAPACITIES:** Opportunities and means to participate (selling, buying, owning) in the money economy (referred to by Karl Marx as the sphere of ‘exchange value’), as a mechanism for material well-being and symbolic enrichment.
- ❑ **POLITICAL AGENCY:** The opportunities and capacities – whether symbolic, deliberative, electoral, or other – to participate in the different dimensions of governance, from family, tribe or local neighbourhoods up to world scale.
- ❑ **AUTONOMY & CREATION:** The freedom and capacity to give — that is, to create and to contribute to others, including artistic creation, music, but also the creation of opportunities for others in society and for other living beings in the wider Biosphere.

This 6-way typology highlights, in a parsimonious way, the material needs (**SUBSISTENCE**) of an individual or group within their wider ecological, economic, social and political context, and also the question of agency (**CREATION**), the capacity of an individual or group to contribute to their wider ecology, politics, economy and society. The individual or group’s needs and capacities — to contribute as well as to take or receive — are characterised across the four system dimensions



of sustainability. Any programme of action or, in our AMORAD context, industrial accident, can be appraised in terms of the ways that it impacts on (or is feared to impact on) the conditions of access (or exclusion of access) of the individual or stakeholder group to resources (capacities for action and expression) in each of the **ECONOMIC**, **ECOLOGICAL**, political (**PARTICIPATION**) and social (**RECOGNITION**) domains.

In application to our AMORAD context or risk governance, we have made some slight adjustments to the original typology of six vulnerabilities, to bring out key points as follows:

- With reference to **Subsistence and Survival**, the vulnerabilities relate not only to food and water, but also to the contamination of people’s homes and habitat; this opens out to the wider domain of environmental life-support services.
- With reference to **Ecological Distribution**, we introduce a sub-division to distinguish the four classes of environmental or ecosystem services already mentioned: (i) natural resources, (ii) waste disposal into the Biosphere, (iv) sensory and cognitive experience, and (iv) life-support services. This is in line with ecosystem accounting fund/flow conventions, and allows us to sharpen the interfacing of socio-economic and environmental considerations.
- With reference to **Political Agency**, questions may be posed about operational capacities (or lacunae) in crisis response and post-accident governance, and also inter-subjective aspects such as the levels of confidence and trust in situations of danger and misfortune.

- With reference to **Autonomy and Creation**, it is impossible to escape from the paradoxes of, on the one hand, the accident as an unintended outcome of intentional human actions and, on the other hand, the role of foresight as capacity building for better preparedness in the case of an (unfortunate) accident.

THE SECTORS OF SOCIOECONOMIC ACTIVITY — THE STAKEHOLDERS OR ‘POINTS OF VIEW’

We have introduced the terminology of environmental and ecosystem services. Services to whom? If Biosphere functioning is perturbed, to whom does it matter? As “stakeholders” in a nuclear technology accident, we distinguish 16 sectors in a relatively conventional way, for a comprehensive coverage of socio-economic activity. These are:

Agriculture and Forestry; Transport and Mobility; Energy; Industry and Manufacture; Waste and Pollution; Water resources management; Natural heritage; Fishing and Aquaculture; Building and Construction; Urban infrastructure; Household consumption; Government and administration (at State/national levels); International coordination activities; Local and territorial administrations; Education and future generations; Research and specific knowledge; Other (if needed).

Matrix ‘B’ — Ex ante Risk Appraisal [FOREBODINGS]

The second framework for *ex ante* evaluation, referred to as ‘Matrix B’, seeks to highlight the social significance of a nuclear accident in a complementary way, by a focus on the nature of the concerns about vulnerability and safety expressed by people across a wide spectrum of socio-economic categories. The axes employed are as follows:

- ❑ **THE POINTS OF VIEW: Sectors of Socio-economic Activity [the same as in Matrix A]**
- ❑ **THE ISSUES: Dimensions of Vulnerability and Capacity [the same as in Matrix A]**
- ❑ **The Objects of Evaluation Attention: THE FIELDS OF WORRY OR PREOCCUPATION**
- ❑ *The Contexts of Knowledge: Historical and Potential Accident Sites [the same as Matrix A]*
- ❑ *The Categories of Knowledge Carriers: Societal Voices of Nuclear Accident Concern*

The first three of these axes (**IN BOLD**) are mobilised by the Deliberation Matrix. By comparison with the ‘Matrix A’ structure, we have modified the objects of evaluation attention. Rather than a classification in terms of Biosphere compartments, we have introduced a typology of the thematic fields of worry or preoccupation in society. (The two other axes are identical for Matrix ‘A’ and Matrix ‘B’.)

The triangulation of these three axes in ‘Matrix B’ means that, in effect, we are considering the risk of an accident directly as a source of worry or preoccupation expressed in society, with reference to the vulnerabilities and capacities of the actors of each socio-economic sector.

THE FIELDS OF WORRY OR PREOCCUPATION [THE FOREBODINGS]

The typology of Objects of Evaluation Attention retained for the ‘Matrix B’ exercise, has been constructed on the basis of our discourse analysis, to highlight the spectrum of “worries” and performance preoccupations expressed in society in relation to nuclear technology and (risk of) accidents. The categories retained are:

Human integrity; Environmental damages; Risk Governance; Ethics; Nuisance/Inconvenience; Technological Performance; Risks/dangers associated with technology; the Symbolic Dimension.

This typology has been obtained as a synthesis of themes identified through the literature reviews and, more particularly, discourse and institutional analyses carried out as background to our AMORAD work (see O’Connor, ed., 2021, AMORAD Deliverable L.2.2.1). Deliberately, we have kept this typology quite close to the “raw material”, with no attempt to overlay it with a strong theoretical interpretation.²⁸

²⁸ A detailed presentation of these fields of preoccupation is provided, in French, as **APPENDIX ‘C’**.

The role of the typology is to provide an empirically grounded axis for organising the “Arguments” in the Deliberation Matrix ‘B’, that is, in triangulation with the more synthetic axes of Vulnerabilities and Socio-economic sectors.

SOCIETAL VOICES OF NUCLEAR ACCIDENT CONCERN

In the background to the Deliberation Matrix ‘B’, two further axes are retained to characterise the sourcing or “production” of the knowledge propositions. These are employed in the KerBabel Representation Rack, but not in the Deliberation Matrix itself. For the axis corresponding to **CONCEPTUAL FRAMES**, we retain, as in ‘Matrix A’, the spectrum of historical and potential accident sites. For the **KNOWLEDGE CARRIERS**, by contrast, we introduce a typology in institutional and sociological terms of *the spectrum of “voices” in society expressing nuclear accident concern*.²⁹ This typology is rather crude, in order to avoid it becoming too cumbersome.

- **Voices of the Peacetime Nuclear Sector (research, exploitation, waste management...)**
- **The Business World (all sectors other than nuclear)**
- **Professional Organisations**
- **Trade and Labour unions**
- **Territorial and National Governance institutions politiques**
- **Official International Organisations**
- **NGOs and Activist Organisations (including anti-nuclear activists)**
- **Other Voices of Civil Society**
- **Viral Voices (Digital Social Networks)**
- **Mass Media (printed press/radio/local & national television)**
- **Scientific Voices – Sciences of Nature (including life sciences)**
- **Scientific Voices – Social sciences and Humanities**

With the ‘Matrix B’ framework, we seek to exploit the spectrum of “opinion” about nuclear accident dangers (in the past and in the present, as the well-springs of propositions that might be mobilised in the *ex ante* exploration of accident impacts. The intention of the ‘Matrix B’ foresight exercise is, once again, to engage in a structured way with the richness of the “potential impact space”, so as to orient precautionary action and to increase preparedness in the event of a future accident.

Bringing Together the Social and Environmental Dimensions

Overall, we can consider the two Matrices as, in a certain sense, portraying (A) the environment dimension, and (B) the societal dimension of accident impacts. **Figure 3** shows the two matrices, ‘A’ and ‘B’, set back-to-back, setting the societal fields of fear and worry in dialectical counterpoint with the biosphere compartments.

The composite picture of *what matters and why*, in the case of an accident, emerges cumulatively through the spectrum of “signals” (including scientific knowledge propositions and other expressions of opinion) emanating from a wide cross-section of knowledge frames and actors in society, mobilised within the corresponding cells of the (double ‘A’ & ‘B’) Deliberation Matrice.

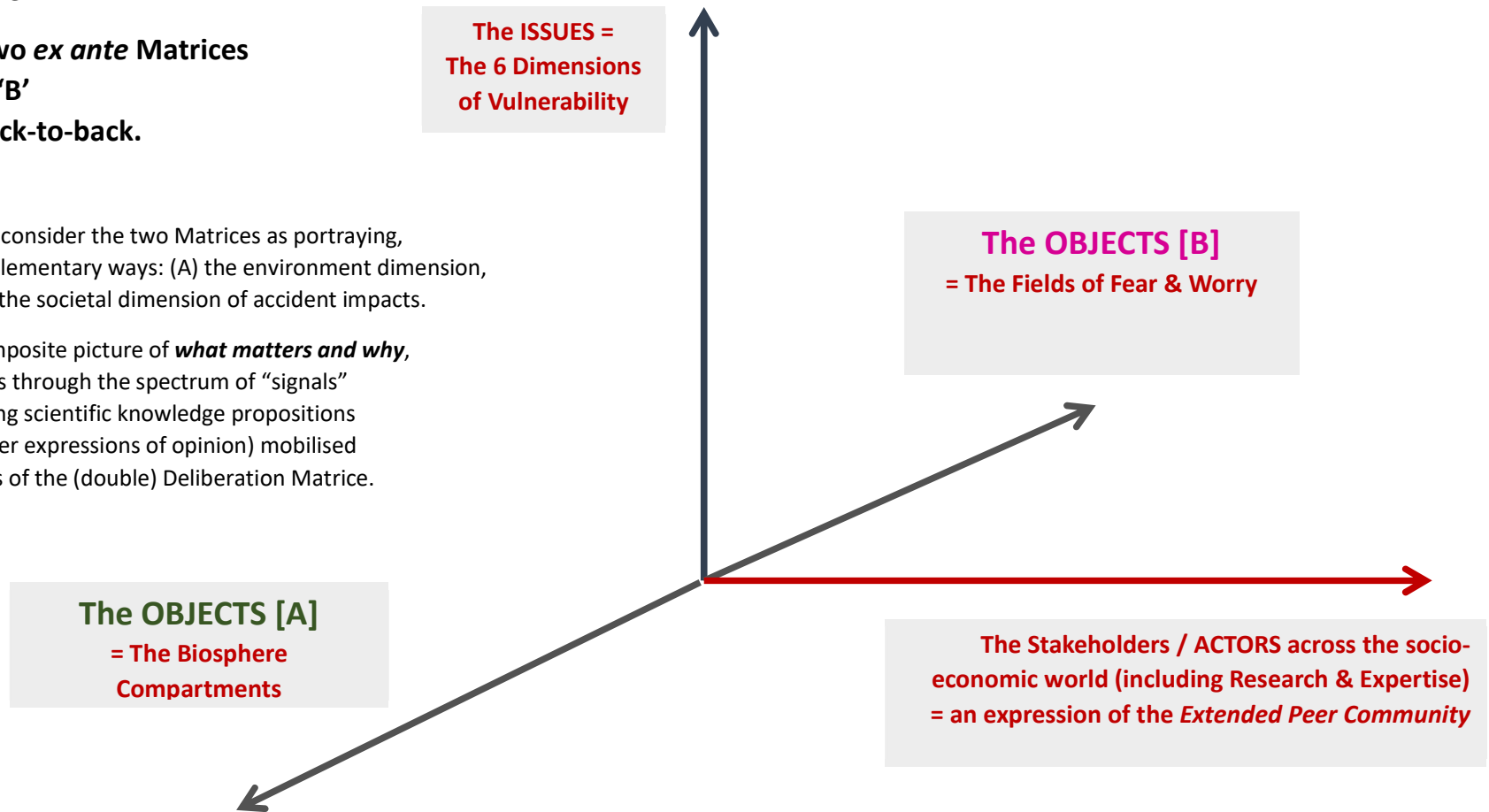
The diversity and extent of impacts of a major nuclear installation accident being so great, across space and time and across the different facets of human well-being and vulnerability, it is impossible to envisage a “complete” inventory. Scientific understanding of the ecological and health ramifications of past accidents (Chernobyl, Fukushima) is still very incomplete; even less is it possible to envisage a comprehensive scenario modelling for all contingencies of a hypothetical future accident. This is why our method is based not on deterministic or probabilistic modelling, but rather on a qualitative profiling — or “scoping” — across the broad spectrum of plausible and possible accident impacts.

²⁹ Once again, this typology is based on the discourse and institutional analyses carried out as background to our AMORAD work (see O’Connor, ed., 2021, AMORAD Deliverable L.2.2.1).

Figure 3.
The two *ex ante* Matrices
'A' et 'B'
set back-to-back.

We can consider the two Matrices as portraying, in complementary ways: (A) the environment dimension, and (B) the societal dimension of accident impacts.

The composite picture of *what matters and why*, emerges through the spectrum of "signals" (including scientific knowledge propositions and other expressions of opinion) mobilised the cells of the (double) Deliberation Matrice.



§11. The Sources and Voices of Knowledge Propositions

The preceding sections offer a framework, both conceptual and operational, for building up a composite representation of what matters and why (and to whom and in the eyes of whom) about a past or conceivable future accident of a nuclear technology installation. In our AMORAD context, this methodological work has been accompanied by, and is in many respects inspired by, our attention to the great diversity of knowledge propositions that clamour to be recognised as contributions to our accident impact synthesis ambition.

Given the contingencies and ramifications of both past and hypothetical future accidents, any notion of a “comprehensive” response to the profiling of impacts would seem chimerical. Nonetheless, it is an essential part of our ambition to highlight the diversity of pertinent knowledge propositions and to demonstrate how the inclusion of a representative diversity of such propositions can be a mechanism not only for collaborative learning by the researchers involved, but also for wider societal capacity-building. In this regard, we have given attention to three broad categories of sources.³⁰

- ◆ Published scientific literature on and around nuclear technologies, accidents and their impacts.
- ◆ Internet sources of information and opinions expressed in civil society (that is, outside the confines of recognised scientific and technical expertise) about the risks and consequences of a nuclear accident.
- ◆ Speculative literature about technology and society.

Works in the last of these categories — speculative literature including science fiction and dystopias (such as Bradbury or Barjavel) — have not been subjected to a formal analysis. They are nonetheless a part of the “baggage” or background that we bring into our scientific work.

For the first category, scientific literature, we make a pragmatic distinction between work carried out and reported by colleagues associated directly with the AMORAD project itself, and the rest of the international scientific community. The work of AMORAD colleagues, directly available to us through reports and internal project meetings well in advance of publications, has in some cases been exploited directly (as in the case of the IRSN *Fiches Marines*, mentioned below), and has also given us an important window onto scientific production world-wide.³¹

Nonetheless, we have also carried out our own review of contributions in peer-reviewed scientific literature review. The search methodology is reported in detail by Douguet (2018). In line with our mission, we sought insights around three questions: What conceptual frameworks are mobilised in the

³⁰ The paragraphs that follow draw, in a very synthetic way, on the material in O’Connor (ed., 2021), *Approche méthodologique et empirique pour établir une vision systémique de la signification pour le système économique des changements écosystémiques suite à un accident nucléaire*. This unpublished report (in French, accessible on Internet) includes the contributions referenced as Douguet (2018), MétaMètis (2019), and the relevant chapter from Tran (2019).

³¹ We should mention the importance of documents from institutional sources (in France and elsewhere), addressing civil nuclear accident risks, consequences and response strategies. Many such documents are unpublished, and they are not always publicly available. To the extent that they are available, we can subject them to scrutiny and cataloguing alongside academic publications. Some such sources are identifiable within the list of documents reviewed (see Douguet 2018, op.cit.). The specific case of the IRSN *Fiches Marines* is further discussed below. In the context of the AMORAD project, we looked at the opportunity of direct exploitation of the rich partner scientific expertise around us, as a source of insights on accident impacts. A framework for consultation and on-line documentation was developed (Tran 2019) which in some ways parallels the KerBabel methodology for digital representation and mobilisation of information categories. Although, for essentially institutional reasons, this idea of a real-time documentation of science-in-action was not fully implemented, it remains a prototype of the challenges, and possible solutions, for the re-insertion (sic) of scientific activity as a resource for the wider societal appropriation of high-stakes risk governance problems.

analysis and evaluation (*ex post* or *ex ante*) of nuclear technology accidents? What sorts of impacts are identified on environmental and ecosystem services? What are, or might be, the principal impacts on society? Seven sets of searches were undertaken, notably targeting the Web of Science and Scopus data bases, in order to pick up a wide diversity of scientific articles covering these three axes, at the levels of concepts, analysis tools, and empirical terrains.

This led to 1867 published texts being identified. After a preliminary reading of the titles and abstracts, 224 of these were retained for further scrutiny. These texts were read in full, leading to reduction down to 55 articles judged to be particularly pertinent. For this selection, detailed analyses were carried out, leading to their classification as sources of “knowledge propositions” classified along multiple axes. These classification axes include, for example, the types of radionuclides (by atom and isotope), units of measure for radioactivity and contamination, categories of damage to health and ecosystems.

On this basis two complementary knowledge documentation actions are undertaken. First, the publications themselves are catalogued, as putative carriers of knowledge propositions. Each of the publications is characterised with reference to the four complementary pertinence typologies set out in the *KerBabel Representation Rack* for the Matrix ‘A’ deliberation (*viz.*, the domains of natural sciences and humanities, the sites of historical or possible future accident, the compartments of the physical environment and Biosphere, and the dimensions of vulnerability). This makes them available — or, more exactly, their meta-information profiles — to be mobilised in a deliberation exercise, as signals in justification for preoccupation in one or other of the cells for an *ex ante* accident impact evaluation.

Second, drawing directly on this pool of publications, it is possible (with the help of students) to incorporate a wide diversity of specific information categories, as “candidate indicators,” represented as digital objects (meta-information profiles) in the *KerBabel Indicator Kiosk* (described previously). These digital objects are thereby available to be mobilised, through the Kerbabel Representation Rack, as signals for exploring and characterising sector-by-sector vulnerabilities, in an exercise with the Deliberation Matrix.

The detailed tables set out in Douguet (2018) present one or more concepts considered pertinent as a “candidate indicator” for each of the 55 scientific publications in our data field.

These catalogues of “candidate indicators,” along with the catalogue of the publications, can be considered as preliminary findings in our scientific efforts at scoping of accident impacts and their significance in society. More importantly, from our point of view, they are classified and made available as a teaching-and-learning resource, useful for initiating students, professionals, or groups in civil society to the character of the risks associated with nuclear technology. This is what we mean by building resources for societal capacity building.

For the second broad category, the perceptions of civil society, a specialised team was engaged during 2018-2019 to carry out a search and synthesis across the internet, using automated techniques of discourse analysis (including precursors of current ‘AI’ algorithms). This work, whose methodology and main results are reported in MétaMètis (2019), has generated a rich data base of discursive elements — short blocs of discourse which are characterised in terms of their origins (document, authors, Internet source, institutional elements), and their subject matter. The subject matter of each extract is characterised with four cross-cutting typologies: societal fields (such as food, energy, safety and security, etc.), the reference topics or targets (for example: radioactivity, nuclear energy, the media...), the geographical or administrative scope (for example, the Fukushima district, Japan, global), and normative concern (human integrity, environmental quality, ethics, risk...).

This data-mining process has led to the identification, in a synthetic way, of a wide cross-section of “arguments” expressed by different actors in civil society around nuclear technologies, accidents and risks. A complete list of the 250 arguments so identified, with corresponding elements of classification, is presented in MétaMètis (2019). Once again, this catalogue of “arguments” can be considered as

preliminary findings in our scientific efforts at the scoping of societal perceptions and preoccupations about nuclear accident dangers. As an intermediate result, they have crucial methodological and pedagogical value.

At a methodological level, the MétaMètis discourse analysis exercise has provided us with baselines for the definition of two key axes in the Matrix ‘B’ [Forebodings] framework for deliberative evaluation. These are the axes of *Fields of Fear and Worry* (the domains of impact), and of the *Voices of Nuclear Accident Concern* (the carriers of knowledge propositions in society). But also, the 250 “arguments” are available to be catalogued and pre-classified in the KerBabel Representation Rack, as a demonstration resource for risk governance deliberation exercises.

At a pedagogical level, the axes for our Deliberation Matrix ‘B’ being established, the catalogue of “arguments” is available to be mobilised, through the KerBabel Representation Rack, as signals for exploring and characterising societal perceptions of risk and vulnerability. This means that the Deliberation Matrix ‘B’ along with the demonstration sample of 250 arguments, are available as a teaching and learning resource, useful for initiating students, professionals, and groups in civil society to the character of the risks associated with nuclear technology.

This brings us back to the core of our vision of risk governance as a challenge of collective capacity building in society. We are not averse to meticulous work at disciplinary levels, for the production of scientific knowledge. Such knowledge is needed, be it of radioactive isotope decay parameters, ocean currents and their variations, fish populations and the time-patterns of contamination, or land cover data for urban and rural territories. Nonetheless, as set out in preceding sections, the accent of the KerBabel knowledge management tools, is on process design for mobilisation of knowledge propositions as resources for collaborative learning (see **Figure 4**).

In the KerBabel methodology, knowledge propositions — of whatever sort — are managed by on-line whose role is to pre-classify Signals in terms of their contextual ‘Fitness for Purpose’ for informing deliberations about situations or scenarios of interest. These meta-data systems — referred to as galleries — are managed within the ‘ePLANETe’ platform. In **Figure 3** we have already set out the differentiation of galleries on methodological terms, distinguishing between:

- **Tools for conducting an evaluation exercise**, notably the KerBabel Deliberation Matrix.
- **Tools for the cataloguing and pre-classification of knowledge propositions**, notably the KerBabel Indicator Kiosk (KIK) and the KerBabel Representation Rack (KRR).
- **Tools for the representation of key features of the objects of evaluation attention**.

We have given examples of documentary analysis and data mining procedures that contribute knowledge propositions of various sorts directly into the KIK and KRR. In these cases, the knowledge propositions have been sources in heterogeneous media, ranging from academic publications to on-line social network discourses. To complete our method demonstrations, we want now to give an example of the purposeful integration of scientific data sets into “upstream” KerBabel tools for the representation of territorial systems.

Our focus for *ex ante* evaluation in AMORAD is on the significance for society (or, in other terms, the impacts on society) of changes in environmental conditions that will or might be provoked by a nuclear accident. Three galleries in the ‘ePLANETe’ platform of knowledge mediation and deliberation support tools are particularly dedicated for the representation of the interdependencies of socio-economic activities with their Biosphere conditions. These are:

- The gallery of “**VIRTUAL BIODIVERSITY GARDENS**” which provides for the profiling (in an intuitive way) and the geo-localisation of any chosen item of the living world, thus building up a smorgasbord of “*bits of biodiversity*” for the territory of interest.
- The gallery of “**TERRITORIAL FOOD BASKETS**”, which provides for a cataloguing of any sort of food supply activity from and/or into a territory. These activities are referred to as *Foodbytes*. Most often, there is

identification of a point of production, a pathway or transportation or transfer, and a point of use or consumption. A picture can be built up of the transactions by which a territory nourishes itself and/or contributes to the nourishment of other territories.

- The “**HERITAGE PARKS**” gallery exploits a systemic fund/flow framework for the presentation of the features of a territory deemed significant from a sustainability point of view. The territory is considered as made up of one or several “*heritage sites*”, each of which is composed of numerous “*morsels*”. These morsels of heritage are classified in a variety of ways, as elements of patrimony — e.g., with natural, cultural, economic significance. They are linked together by *transactions* (also classified in various ways) which can contribute to the sustaining or degradation of the morsels. Values are identified in a patrimonial perspective, with a view to their vulnerabilities.

In our AMORAD work these galleries have been exploited for building up an inventory of items of significance for each of the reference territories of zones at risk. This is an immense task, and we do not seek a “complete” or comprehensive inventory. Rather, we aim for didactic clarity. Notably, we can exploit pre-existing sources of information, of many types, so as to integrate into the galleries a representative diversity of “bits of biodiversity”, of “foodbytes”, and of heritage “morsels” and “transactions” deemed to characterise the territory and its vulnerabilities.

We give one example of the sorts and sources of data. This is the set of **Fiches Marines** (maritime area profiles) developed by colleagues in the IRSN (the AMORAD Project coordinator). The intention has been to create a ‘Fiche’, for each of the zones at risk in the French metropolitan territory, meaning eleven in all. These include the river mouths and coastal zones that are downstream from nuclear power stations, and also the coastal zones close to military and peacetime nuclear technology installations (Toulon, Brest, and the Cotentin).³²

Each ‘Fiche’ sets out sets of information and corresponding maps for the following categories of systems, human activities and vulnerabilities:

- The estuary zones for the rivers that host nuclear installations upstream.
- Physical characteristics of the estuary and coastal zones, including geology, depths, currents, tidal variations
- Key features of the human populations and economic activities in the zone, and associated vulnerabilities, including health risks.
- Beaches, bathing and diving areas.
- Fishing and aquaculture activities, including catch volumes and water takes
- Thalassotherapy installations
- Extraction of sea salt (and any other mineral extraction)
- Port areas and associated activities (commercial freight, fishing, passenger services, cruise lines, yachts and recreational motor-boats)
- Ecological features and notable ecosystems (coastal and marine)
- Natural protected areas (e.g., marine or coastal biodiversity reserves).

Although this list is rather heterogeneous, it allows us to see how the Fiche Marine for a territory provides a wealth of information that can readily be incorporated as digital object profiles in one or other of the ePLANETE galleries mentioned above. We have carried out this integration on an experimental basis, so as to build up a composite digital picture of the natural and socio-economic wealth of a territory, of the multiple flows of “services” that this wealth provides, and thus of the vulnerabilities to damage and disruption in the case of an accident. Once compiled, these on-line catalogues are available as pedagogic resources, for initiating students, professionals, or groups in civil society to the character of the risks associated with nuclear technology. Moreover, the galleries can be enriched progressively, by students or other stakeholders working in a collaborative way.

³² The methodology for creation of a ‘Fiche Marine’ is set out in several documents, including IRSN (2018) and Louis (2021). Complete Fiches have been produced for the Rade de Toulon, for the Cotentin district, and for the Rade de Brest (see Louis, Duffa & Radakovtich 2021a, 2021b). Full source details are given in **Appendix ‘E’**.

Figure 4 — Functional Organisation of a Gallery in ‘ePLANETe’

Each gallery is composed of collections of digital objects, composed with the CMS Drupal.

Figure (4a). A typical gallery of digital objects has the following structure:

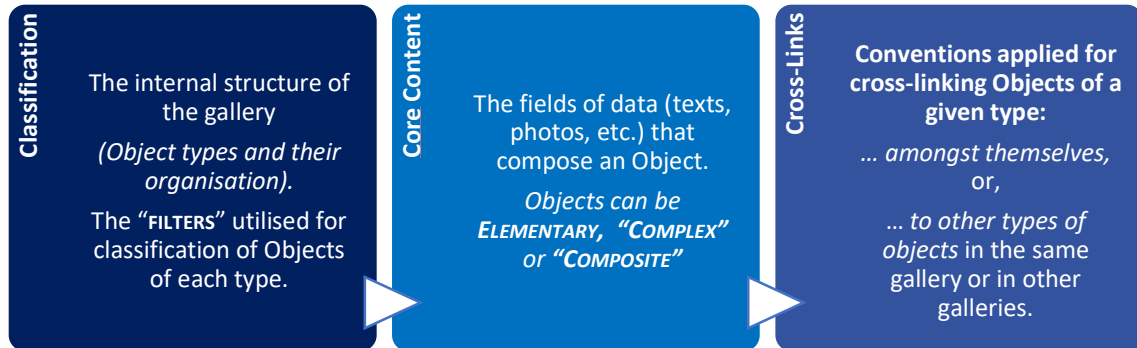


Figure 4(b). In operational terms, the contributions by users of a gallery in ePLANETe, fall into three main forms:

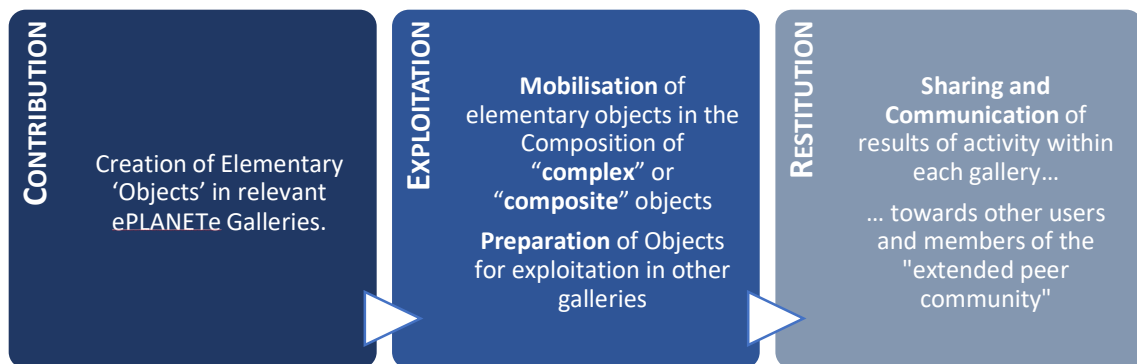


Figure 4(c). The technical operations by members of a User Community, are to be understood in a wider framework of integrative analysis and collaborative learning, set out as follows:



Source: The authors.

Conclusion:

THE IMPACT OF ACCIDENT ASSESSMENT ON SOCIETY

The evaluation of vulnerability *ex ante* of a territory to a nuclear technology accident choice will not, as a rule, produce a clear and simple profile of impacts. Nor would an evaluation of preparation and response strategies (whether *ex ante* or *ex post*) lead to a clear-cut conclusion about what are the right options for action. Such evaluations might, at best, permit partial rankings, for example with reference to one dimension of vulnerabilities, or from a single sectoral stakeholder's point of view.

Consider the well-known theory of justice put forward by John Rawls (1971), by which an action is just if it improves the well-being of the worst-off individual or category of society, and 'unjust' if it worsens the well-being of the least well-off person or category in society. We may then adopt the convention that a person or group making a judgement about an event or a response strategy being adverse or unacceptable, must somewhere be declaring either themselves or another category of stakeholder (for whom they claim to speak), as being excluded from or deprived of some basic need or right. In other words, they are being made unacceptably poor or vulnerable, in some way. This can be an efficient way of structuring a stakeholder consultation process and of building a synthesis of available data of stakeholders' attitudes around a situation of controversy. It does not make divergences of opinion go away, neither about the gravity of the situation, nor about what should be done. Rather (using Rittel's term), it is simply a good way to "*build the problem*".

The role of the Deliberation Matrix frameworks 'A' and 'B' is not to provide a decisive "silver bullet" clarity on what matters and why. Rather, these frameworks are proposed as **deliberation support tools** providing participants in the process with a common framework, with an opportunity of "collaborative learning," and with an opportunity for obtaining new insights into the tensions and dilemmas associated with the "unmanageable" risk governance situations.

Moreover, an evaluation exercise *ex ante* does not simply provide knowledge about an accident's impacts in a hypothetical future. In an obvious way, the exercise of "foresight" (*ex ante* evaluation, the appraisal of risks and impacts of nuclear technology accidents) itself impacts immediately on society, **even if no accident takes place**. A foresight exercise provides insights, by design, into multiple considerations of prosperity and vulnerability of the society. As such, it modifies the conditions of present-day action.

On the one hand, we speculate about different "states of the world" as possible outcomes of an indeterminate complexity. On the other hand, we explore the question of our capacity to intervene in causal sequences (before and after an eventual accident) and influence the outcomes. We appeal to causality in two contrasting ways: in seeking out relations of cause-and-effect; and through the importance that we attach to the notions of informing and justifying our choices as free and responsible actions.

In conclusion, we insist again that the purpose is not to provide a unique answer to the questions of a nuclear accident impact. Rather, retaking the formula of Rittel (1982), an analyst becomes like a "*midwife of problems*". Evaluation is understood as a negotiation process,

"... one of raising questions and issues towards which you can assume different positions, and with the evidence gathered and arguments built for and against these different positions."

In situations of controversy there is typically a clamouring from a wide spectrum of stakeholders, each affirming their own interests, rights, needs and vulnerabilities, and also their principles, precepts and "values" for the respect (or not) that should be accorded to the claims of others (including "future generations" and non-human life that do not have human voices of their own). This clamouring, which

quite often becomes a cacophony (as in electioneering, or in public meetings, and above all on today's digital social network tools), cannot be reduced to an angelic harmony. But we can try to provide a synthetic representation of this clamouring.

The intention of an accident foresight exercise, as set out in this chapter, is to engage the participants in a structured way with the richness of the “potential impact space”, so as to orient deliberation about possible precautionary actions, to increase preparedness in the event of a future accident, and to contribute to societal, as well as biophysical conditions for conviviality and solidarity.

Importantly, we engage in the production, mobilisation and sharing of deeply different, but complementary types of knowledge propositions. Across the different facets of our integrative analysis method, we give priority to a ***qualitative specification of categories of knowledge***, notably concerning categories and attributes of systems, and the postulated causal relations and effects. This is an important change of emphasis, relative to conventions of quantitative measurement, analytical modelling and estimation that often have primacy in scientific disciplinary domains. We are not saying that meticulous attention to measurement, and to identification of cause-effect relations is without importance. Quite the contrary is true. As is evidenced by our own review enquiries into salient scientific literatures, deterministic analyses, as well as probabilistic approaches simulations based on statistical correlations, bring essential insights to risk governance, from multiple disciplines and at multiple scales. The point is that such approaches can never provide a “complete” specification of risks, and they cannot resolve the inevitable dilemmas of judgement and action at the heart of the governance of risks.

One facet of the incompleteness of our knowledge base is very easy to characterise. It is inconceivable, in practice, to obtain high quality quantitative data for every possibility of induced system change and for every aspect of feared or declared vulnerability — neither in the phase of *ex ante* foresight, nor in the phase of *ex post* (crisis and post-crisis) appraisal. Moreover, it is impossible for any ordinary person to assimilate the complexity of data and concepts across all perspectives and levels of observation. Specialists engaged in patient listening, reflection and analysis, can arrive at synthetic understandings; but these are never complete, and can be shared only imperfectly.³³

There is a deeper aspect of incompleteness. As set out in our PART I, multi-disciplinary science teaches us that, in complement to identifiable cause-effect relations, there is an irreducible ***contingency*** in the emergence, stabilisation, and transformation at every scale of geological, chemical, biological and ecological forms of organisation. This inherent element of indeterminacy of “natural history” is then compounded by the human dimension of conscious reflexion and deliberate action. Impact assessment exercises are not only imperfect (in the Cartesian or Laplacian senses), but are in some ways paradoxical, because their destiny is, irreducibly, to be overtaken by real actions and contingent unique events.

By presenting a nuclear technology risk governance situation as *an unresolved controversy*, structured nonetheless as an ongoing process of multi-actor multi-criteria evaluation, we portray the protagonists, including ourselves, as contributors to a collective knowledge resource, united in a spirit of collaborative learning and capacity building. Whether and to what extent this unity is experienced inter-subjectively as a solidarity, is of course a quite different question.

³³ Some people might signal the opportunities of ‘AI’. But in fact, for situations of risk and controversy, the use of algorithms to generate syntheses of knowledge propositions will serve above all to deepen two known difficulties in knowledge quality appraisal: first, how to “verify” the propositions made by ‘AI’ independently of ‘AI’ itself; and second, the limits and biases of human capacities to engage with the outputs of “machine learning”. These deep challenges warrant a separate analysis and discussion.

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APPENDIX A

Short Presentation of 'MARIN' in the AMORAD Project

The general focus of the 'MARIN' component of AMORAD was the study of radionuclide transfer in sediments and food chains, and vulnerability of coastal areas to accident situations.

The general purpose was to improve methods for predicting and assessing the impact on the marine environment (water, sediments and organisms) of an accidental release of radionuclides. The marine environment is often considered to be dispersive, i.e. to rapidly dilute contamination. However, large concentration 'pockets' can occur in some compartments (e.g., radionuclides trapped in sediments, bioaccumulation in parts of biological chains), and major processes can occur at time scales and across distances that are difficult if not impossible to predict with precision in advance. Examples of variability are wind and weather conditions, seasonal variations in temperatures and land cover (e.g., deciduous trees, snow, or waterlogging), tidal cycles and ocean currents, intermittent events like floods and storms that might cause the resuspension of contaminated sediments, intermittent supply by rivers leaching contaminated basins, and so on. Four major 'test areas' have been the object of scientific studies:

- in Japan, the area subject to releases from the Fukushima Dai-ichi nuclear power plant;
- the Channel near coastal nuclear power plants and the spent fuel reprocessing plant at La Hague;
- and the Bay of Biscay and Gulf of Lion which are supplied by rivers on which nuclear facilities are located.

Transfers at the continent-ocean interface and the transport of particles over different time scales and distances have been studied in these areas, which function differently and so enable a diversity of processes and system dynamics to be investigated.

- For the English Channel, a model has been developed to simulate the transport of all sizes of sediments. In particular, it can be used to determine what happens to fine sediments trapped in a matrix of pebbles. This type of heterogeneous sedimentary deposit, which is observed in coastal areas with strong currents, had not been taken into account by previous models.
- The behaviour of radionuclides in a macrotidal estuary (with large tidal ranges) has been studied in the Garonne-Gironde system, on the banks of which the Blayais and Golfech nuclear power plants are situated. The main purpose of this work was to combine laws of behaviour for insoluble species and particles related to the movements generated by tides with chemical laws for the adsorption/desorption of these species, linked to the different composition of river and marine waters. Although the chemical behaviour controlling the adsorption of radionuclides onto particles is an important parameter for explaining whether they are transported to the open sea or retained in the estuary, it is now apparent that the river's flow rate also has to be taken into account. Movement of the maximum turbidity zone in this system is critical to the dispersion of any accidental releases from these power plants.
- The role played by benthic fauna (living in and on the sediment) and storms in sediment deposition and rearrangement has been studied in the Rhône River delta, an ocean-continent interface with a small tidal range (the Mediterranean Sea). These studies have characterized the suspended matter in the river's plume out at sea, including sorption and settling velocity, and the modelling now takes account of these parameters, improving the prediction of what happens to these particles. Measurements of ¹³⁷Cs and of Pu in sediments at the mouth of the Rhône have characterized the variability of accumulation. Whereas deposition in this area takes place mainly over short-term period during floods, the long-term accumulation is controlled by sediment remobilization processes influenced by currents (storms) and benthic organisms that mix up the sediment. These processes remain intrinsically very difficult to predict over time.

The transfer of radionuclides in food chains, and the sensitivity and vulnerability of the affected ecosystems, have been studied for isolated organisms (oysters and tuna) and for entire food chains from the dissolved phase up to tuna and shark.

The study of 'historical' data sets for radionuclide concentrations in various marine organisms sampled in the English Channel (seaweed, molluscs, crustaceans, fish) has determined their biological half-life (the time taken to eliminate half of the radioactivity in these organisms). This is seen as an important parameter to incorporate into 'biokinetic' models, which provide a quick (although approximate) method for assessing changes in radioactivity over time when managing an accident. Maps of contamination risk indicators have been drawn up

for different tuna populations off the Japanese coast based on hydrodynamic models giving the concentrations of radiocesium in the water and models for radiocesium transfer to the prey of tuna (zooplankton, crustaceans, small fish). These maps are subject to change over time. A model taking into account the entire trophic network has been developed for the Fukushima area. It shows how the concentration of a specific radionuclide changes over time and space for a given species, based on fishing areas. The model takes 56 biological groups into account, from phytoplankton to tuna. After comparisons of model results with data obtained over several years for the Japan marine environment, experiments are being made for its adaptation to French coastal zones, notably the Gulf of Lion.

In parallel with the data and environmental modelling work, several decision support methods were explored with the intention of providing prototype tools for use in operational emergency response situations and in post-accident conditions.

- The first of these was based on the spatialization and assessment of different (economic and environmental) risk factors, with conventions to aggregate these data so as to create an “impact map” for the effects of contamination following an accident.
- The second tool, a type of expert system, exploited existing measurement databases to create “default” scenarios for radionuclide redistribution in the aquatic phase, as a benchmark to help with diagnosis and prognosis in post-accident situations.
- The third approach, reported in the present publication, has proposed a method for identifying and assessing, in a multi-criteria multi-stakeholder framework, the significance for socio-economic activity of the ecological and wider environmental changes that might be provoked by a nuclear accident.

CONTI — Study of radionuclide transfers in continental environments

The CONTI component of the AMORAD Project aimed to provide better understanding of and to quantify the processes of radionuclide transfer in forests and in the drainage basin-river at different time scales. The guiding idea was that, if radioactive contamination of vegetation, water and soils can be predicted, then different sorts of impacts for society can be estimated. For example, the loss of usefulness of forest and water resources if contaminated, the costs (monetary and otherwise) and inconvenience arising from obligations to stop drinking water supply and irrigation in the wake of a severe accident at a nuclear power plant.

Data on the resources and their patterns of exploitation must be collected and validated at appropriate spatial scales. This is not a simple undertaking, as some data are available on a local scale, and others only at a more aggregated (national) scale.

Detailed analyses have been made of erosion/run-off flows from drainage basins into rivers and then into the marine environment in the post-accident Fukushima area affected by fallout from the radioactive plume. A modelling method was developed to quantify radionuclide export from the drainage basins to the sea. The model was created to simulate soil erosion and predict the transfer of the contaminated sediments in the drainage basins, while taking account of the different types of land use and hydroclimatic forcing including floods.

The biogeochemical cycle of radionuclides in forest systems has also been characterized, making it possible to model the evolution of Caesium in the different compartments. Data has been collected within an 80 km radius of the Fukushima plant, and, for comparative purposes, near Chernobyl and from various French forest sites. At Fukushima, caesium-137 activity levels rapidly decreased in trees in the years immediately after the accident, but increased in organic layers and minerals in the soil (transfer by falling leaves, liquid fluxes); a stabilisation and progressive reduction of these levels is expected during the coming years.

As a result of this work, the TREE4 model for predicting the evolution of caesium-137 stocks and concentrations in the different compartments of a soil-tree system is now operational. This work becomes an input into the investigation of radionuclide transfer processes in continental environments (soil-forest) and in drainage basins, through soil erosion. For this purpose, the BRGM’s existing Watersed simulation model has been enhanced by the addition of a module for radioactive caesium, then tested on data from a Fukushima drainage basin, in order to provide a basis for calibration of the model for French catchment systems.

APPENDIX B

STRUCTURE AND USAGE OF THE KERBABEL DELIBERATION MATRIX

[B.1] Frames for Deliberative Evaluation: Some Elements of Genealogy

The **Deliberation Matrix** concept was given a prototype multi-media implementation, during 2001-2002, in the context of the EC-funded multi-partner **GOUVERNe** project on interactive tools for integrated management of underground water resources.³⁴ In its ambition at that time, it was proposed as an innovation at the interface of experimentation with (1) the new digital technologies for “web services”, and (2) the preoccupations for stakeholder participation in action-research programmes of integrated environmental assessment.

The years 1990-2010 were characterised by a plethora of experimentations with evaluation frameworks making explicit the plurality of values (implying multiple evaluation criteria) and the plurality of classes or components of society (implying the pertinence of multi-stakeholder and deliberative perspectives). O’Connor & Douguet (2024) have reviewed some of the formulations since the 1990s of “matrixial” approaches to knowledge-values-action problems. In the paragraphs that follow, we provide a condensed version of this review.

Looking at the 3-dimensional array [WHO x WHY x WHAT], as in the schematic figure of the KerBabel Deliberation Matrix, we can consider it as a composite of the two-dimensional structures that can be obtained as “cuts” along orthogonal planes. There are three component forms, each of which has been exploited in literature since the 1990s for the framing of evaluation exercises. For example:

Mephram (1996, 2000) had proposed an “*Ethical Matrix*” for the interfacing of ethical principles (WHY) with interest groups or stakeholders (WHO).

De Marchi, Funtowicz, Lo Cascio & Munda (2000), who sought to align participatory processes with formal multi-criteria evaluation, set out a “*Multicriteria impact matrix*” considering options against performance criteria (WHAT x WHY), and an “*Actors’ impact matrix*” (WHO x WHAT).

Giampietro & Bukkens (2015) have referred to these “cuts” as, respectively, the “*Ethical Matrix*”, the “*Impact Matrix*”, and the “*Equity Matrix*” (also known as the “*Actors’ Impact Matrix*”), attributing them to distinct pedigrees/authors. Their purpose was to explore the possibility of integrating these (and other) tools that, in their observation, were in use separately in the field of participatory integrated assessment.

Bringing together these 3 “cuts” by their integration into a 3-dimensional array [WHO x WHY x WHAT] would then seem to be an obvious step of methodological synthesis. This took place during 2001-2002 in the context of the GOUVERNe Project, with the exposition of the prototype “KerBabel Deliberation Matrix” as the architecture of an on-line deliberation support tool, subsequently referred to as KerDST.

Documentation of the first prototype of the on-line Deliberation Matrix, referred to as the “*Champigny DST*” (dating from 2002), is provided by Amorsi (2013). A bespoke version of the Deliberation Matrix, embedded in a virtual reality environment, dating from 2004, permitting user participation in a comparative multi-criteria multi-stakeholder evaluation of agriculture and underground water resource quality policy scenarios, was developed as a case study in the VIRTUALIS Project (Douguet et

³⁴ The **GOUVERNe** Project (*Guidelines for the Organisation, Use and Validation of information systems for Evaluating aquifer Resources and Needs*: Contract No. EVK1-CT-1999-00043, European Commission 5th Framework Programme, Thematic Programme: Environment and Sustainable Development, was coordinated by Martin O’Connor (C3ED, France) and ran through 2000-2003.

al., 2005). The generic Deliberation Matrix structure, programmed since 2005 with the Open-Source DRUPAL CMS software, is presented in O'Connor (2006), referring back to the GOUVERNe and VIRTUALIS prototypes. Detailed methodological presentations were, at that time, provided in the institutional working papers by O'Connor, Bureau & Reichel (2007), and Reichel, Bureau, Legrand, O'Connor & Sunde (2007), available on-line.

	WHO	WHY	WHAT
WHO	<i>Stakeholders</i>	"ETHICAL MATRIX" Mepham (1996, 1999) Kaiser & Forsberg (2001) Schroeder & Palmer (2003) Palmer (2003)	"EQUITY MATRIX" De Marchi et al. (2000) Munda (2008)
WHY		<i>Issues</i>	"IMPACT MATRIX" Munda (2004, 2005, 2006) De Marchi et al. (2000)
WHAT			<i>Options or Scenarios</i>

[B.2] Variants of the KerBabel Deliberation Matrix

In general terms, the **KerBabel Deliberation Matrix** permits a didactic presentation of the process and outcomes of *judgements* offered by each category of stakeholders, for each of the options or scenarios under evaluation, with reference to a *spectrum* of governance or quality-performance issues. The principle, is that that *each* stakeholder class should offer a judgement (e.g., *satisfactory*, *poor*, *intolerable*, etc.) of *each* option/scenario in relation to *each* of the key governance or decision issues.

One obtains in this way, for each stakeholder (or actor class), a rectangular array of cells, being a layer of the Matrix, within which each row represents (issue by issue) the evaluations furnished by the given class of stakeholders for successive options/scenarios. Or, looked at from another angle, one obtains the evaluations by each stakeholder, of a given option/scenario.

Since 2005, several KerDST variants are available for the composition of an Evaluation Exercise. The simplest procedure, which can be carried out on paper or on line, is that of "Colouring in the Cells" by single representatives of each stakeholder category (or by a single expert acting "on behalf" of all stakeholder categories) for a qualitative multi-stakeholder multi-criteria assessment of a situation or of options for action.

The "default option" suggested for colour codes is the "traffic light" convention of RED for bad, YELLOW for moderate, and GREEN for good; but KerDST users can define their own list of judgement categories and corresponding colours. For the more complicated variations of KerDST, this method of "scoring" or signalling by colour to build up a three-dimensional array of qualitative judgements is preserved, but with conventions for the "composition" of the cell-level signals. The simple procedure can thus be enriched,

- On the one hand, with variations where several participants within each stakeholder category contribute to provide a "composite" judgement per issue (that is, with several colour signals per cell); and,
- On the other hand, towards mechanisms for "deepening" the knowledge resources, where representatives of each stakeholder category (or experts acting "on behalf" of stakeholder categories) work to produce an evaluation supported by indicators, thus linking indicators to each nexus of stakeholder category and societal performance-quality issue.

In the case of an indicator-supported evaluation, it is necessary to compile a '**BASKET**' OF INDICATORS that, in the eyes of the stakeholder, signal key attributes of the object (scenario/choice or

activity/site/territory) under scrutiny, relative to the performance issue. The judgement at the cell level in the Matrix is thus obtained not by a simple choice of colour for the cell, but as a weighted “amalgam” of the qualitative judgements assigned to each indicator in the “basket”. Detailed illustrations of indicator-based evaluations using the on-line Deliberation Matrix are found in Maxim (2008) and Aydin (2017).

In the 2006 KerDST, it was permitted to choose UP TO 5 DISTINCT INDICATORS for each “basket” corresponding to a Cell. This was a deliberate restriction, whose purpose is to incite contributors to identify what are the “key” signals that, for each cell in their slice of the Matrix, they wish to bring to the attention of others.

For each indicator placed in a basket, the user must specify the JUDGEMENT [by choice of colour code] and also the relative WEIGHT compared with other indicators in that basket. The colour shown for each Matrix cell is then a function of the relative weights and normative significance attributed to each indicator in the corresponding basket. The convention since the 2006 on-line version of KerDST, has been that the cell itself takes the colour that has the highest percentage within in the “basket of indicators”. This convention was adopted, after some experimentation during 2004-2006, for its didactic clarity. It tends to produce clear visual contrasts between cells and also, at the next level up, between rows or columns of cells in the Deliberation Matrix, or again, between entire layers (or “slices”) of the Matrix.

These KerBabel Indicator Kiosks (KIK for short) are, since 2004, composed and managed by a Content Management System (successive versions of the CMS Drupal), now integrated within the vaster ‘ePLANETe’ platform (Lanceleur 2019). The KIK functionality in KerDST (embedded since 2013 within the ‘ePLANETe’) provides for comprehensive profiling of an Indicator concept and of sources and uses of empirical data in empirical applications. But, the emphasis being on ease in the definition and mobilization of a system attribute deemed of descriptive and normative pertinence, only a very limited number of meta-information fields are obligatory for the creation of an “Indicator” profile in a KIK.

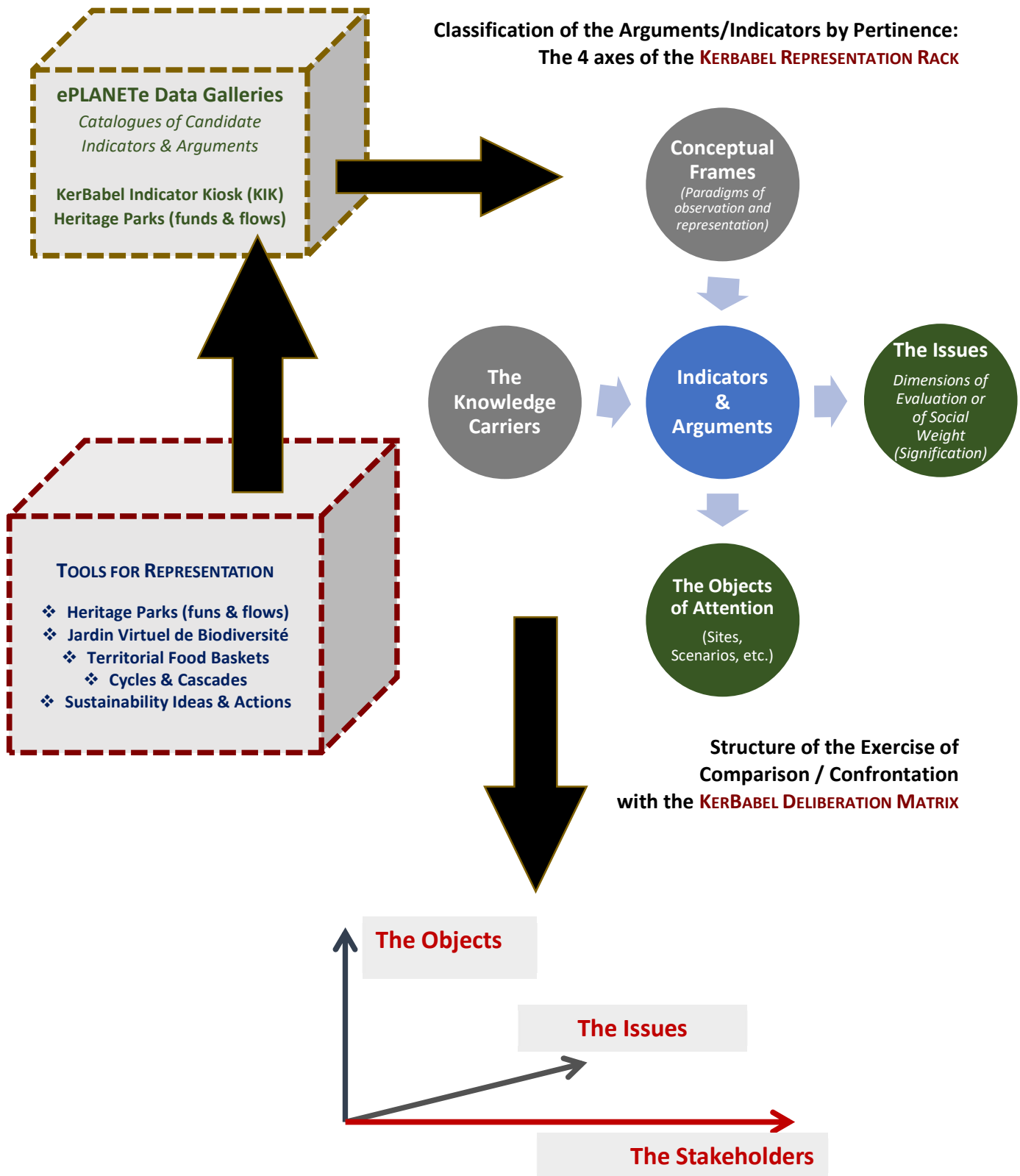
- The KerDST users are invited to signal the inclusion of *indicator concepts* within each Deliberation Matrix cell or “basket”. That is, they are invited to signal the selection of “objects” from collections that are presented with succinct meta-information profiles (the Indicator’s Identity Card, as it were) in catalogues that are available as satellites to the Deliberation Matrix itself.
- This means, importantly, that the KerDST user is not required immediately to search for data corresponding to an indicator, nor to verify/validate others’ data. Rather, the contribution at cell level the KerDST evaluation process is made by mobilising objects described with *meta-data*.

Digital technology has advanced in leaps and bounds since the early KerDST prototypes. During 2023-2024, the KerBabel deliberation support tools have been entirely re-engineered, within the Drupal-10 CMS environment, without changing the basic concepts of deliberative evaluation structure, but introducing several complementary features made possible by the advances in ICT.

- Pre-classification of signals in the KRR.
- Generalisation of the galleries as sources of signals
- Experiments with the exploitation of ‘AI’ [Automated Imbecility] for (i) the selection of signals to be incorporated at the level of the individual “cells” of a Matrix, and (ii) the generation of propositions for the categories to be aligned along each of the axes constitutive of a deliberative evaluation problem.

The last of these innovations is ongoing, as it involves notably the incorporation of design solutions for the deliberate and explicit “interfacing” of human judgements about the pertinence and knowledge quality of the propositions generated by ‘AI’.

The Core of the KerBabel Deliberation Process



APPENDIX C

THE FIELDS OF PREOCCUPATION FOR THE ‘FOREBODINGS’ MATRIX

Section §10 of the main text lists in succinct terms a typology of Objects of Evaluation Attention retained for ‘Matrix B’. The categories, obtained by the authors on the basis of discourse analysis, highlight the spectrum of “worries” and performance preoccupations expressed in society in relation to nuclear technology and (risk of) accidents. In more detail, the categories retained are:

- **Human Integrity** : Ce domaine d’action met en avant la question des menaces qui peuvent porter atteinte au corps physique des personnes (radiations subies, développement de maladies, de cancers,) et à la vie humaine (mortalité, effets héréditaires, reproduction, troubles psychologiques). Il s’agit également de question relevant de la dignité, du droit à une vie décente et de l’autonomie de la personne. Elle se mesure également en termes des mesures mise en place suite à une catastrophe.
- **Environmental Damages** : Les dommages environnementaux désignent des changements négatifs qualitatifs, quantitatifs, fonctionnels de l’environnement. Les divers compartiments de l’environnement (Biosphère, hydrosphère, atmosphère et lithosphère) sont à considérer ainsi que la diversité des services écosystémiques (Sources, Puits à déchets, Support de vie et Appréciations cognitives). Ces dommages environnementaux sont compris comme étant les pressions exercées par l’activité humaine sur les milieux naturels.
- **Risk Governance** : La gouvernance des risques renvoie à un système d’entités décisionnelles, mobilisant une diversité d’acteurs, dans le cas présent, institutions privées (secteur industriel nucléaire), des institutions publiques (de régulation et de gouvernement, de recherche...) mais peut également inclure des ONG et des représentants de la société civile (sous la forme de gouvernance inclusive), afin de diriger le domaine du nucléaire au niveau nationale et international. Elle repose notamment sur l’identification, l’évaluation et la hiérarchisation des risques ainsi que la mise en œuvre de processus politiques (système d’alerte, de mise en œuvre de stratégie de crise, surveillance du parc nucléaire, identification des responsabilités en cas d’accident ou de catastrophe...).
- **Ethics** : La question éthique nous interroge sur les processus sociaux portant sur la valeur des pratiques et des conditions de ces pratiques ainsi que la moralité des actions. Elle porte, dans le cas présent, sur les questions de production et de diffusion des connaissances (fourniture par des entreprises de rapports falsifiés aux pouvoirs publics), sur les questions de santé (choix relatifs aux traitements différenciés selon la population, santé mentale des travailleurs du nucléaire (responsabilité, sentiment de culpabilité)), sur les questions de choix politiques (maintien de la technologie nucléaire, orientations dans les choix d’investissement, de compensation, méfiance envers les pouvoirs publics et les entreprises...).
- **Nuisance/Inconvenience** : La question de inconvénients est comprise comme étant l’identification des changements négatifs, qualitatifs, quantitatifs et fonctionnels dans la société (destruction de zones d’habitation et d’activité économique, migrations de population, fourniture d’énergie...)
- **Technology Performance** : La performance technologique renvoie aux questions de sûreté et de sécurité que ce soit au niveau de la manipulation, au transport, au stockage de matières dangereuses (eaux contaminées) et des rejets d’éléments radioactifs pouvant impactés la santé humaine (irradiation) et l’environnement (contamination). Elle touche également aux solutions de traitement et de dépollution des sites accidentées et des solutions de substitution (pour produire de l’énergie par exemple).
- **Risks/dangers associated with Technology** : Les risques associés à la technologie sont ceux liés aux caractéristiques de la zone (immergeables, séismes...), l’accès aux ressources nécessaires pur le fonctionnement de l’entreprise ou du territoire (mines uranium...), à la dégradation de l’environnement (contaminations des chaînes alimentaires, niveau/normes) et des risques pour les humains (cohésion de la société, mouvements anti-nucléaires, alimentation...),
- **The Symbolic Dimension** : Le symbole revoie à la représentation subjective, au sein de la société des images, des écrits, des actions entreprises par des institutions publiques, des institutions privées, des ONG, des acteurs de la société... avant, pendant et à la suite d’une situation de crise nucléaire. Elle ne repose pas sur des faits scientifiques ou techniques mais sur des perceptions au sein de la société. Elles peuvent faire l’objet de jugements fallacieux (infox), de biais cognitifs...

APPENDIX D

RADIOACTIVITY STEWARDSHIP ETHICAL BOTTOM LINES

The question “*What to do?*” in a crisis or post-crisis situation is characterised by numerous “Known unknowns” and by dilemmas where the response to one urgency seems likely to worsen outcomes on some other point, each urgency seeming nonetheless an imperative from the relevant stakeholders’ points of view.

No proposed action will be “perfect”, and all propositions for action will be open to criticism from some points of view. The challenge, nevertheless, is to maintain social cohesion and solidarity – not only for the immediate needs of crisis response, but also as a precondition for the necessary reconstruction and future prosperity.

One important part of building up capacity and resiliency is to deepen our understanding of the nature of such dilemmas as characteristic of situations of risk governance. In this vein, we can envisage evaluation exercises where participants are invited to explore and to contribute in the formulation of justifications for – and against – specific actions and strategies in a post-accident situation. This is not in order to have the final word on public policy decisions, but in order to build the necessary capacity for engagement in multi-stakeholder deliberation and debate.

Many frameworks are available to make explicit the complex normative dimensions of risk governance actions. As we have discussed at length elsewhere (O’Connor & Douguet 2024), the ‘ethical’ dimension of risk governance consists not of a simple or unique criterion of what is good and right, but rather of ***the articulation of the spectrum of normative principles*** that, one way and another, stakeholders bring to bear in their cacophony of judgements about the “wicked problem” being addressed.

The typologies of vulnerabilities already set out in the main text, is one such framing. Another framework, shown in the table on the following page, adapted from O’Connor (2009), sets out a synthesis of considerations of performance and responsibility that have typically been suggested for radioactivity site stewardship.

We adopt a neologism and refer to the **ETHICAL BOTTOM LINES** for an appraisal of opportunities for action. The table proposes a compilation of ‘ethical bottom lines’ in the form of questions, with seven key precepts whose scope, in each case, is explained and illustrated by a second tier of “sub-principles”.

Any action proposed, either as a matter of precaution or as an ex post response after an accident, has the status de facto of a “candidate” put forward by project holders towards the rest of society, as an ***ethically principled action*** — that is, an action that is intended to satisfy or respond to particular criteria of good or sound practice that are suggested by at least some members of the society. But, just as “*one man’s meat is another man’s poison*”, we must allow that different ethical bottom lines enter in collision and cannot always be reconciled.

Sources: O’Connor (2009). The initial ‘Ethical Bottom Lines’ checklist concept for radioactivity site stewardship was developed in O’Connor (2003), drawing on insights from Fleming (2003). Some preliminary considerations are set out in Faucheux & O’Connor (2005), and the full ‘checklist’ as it appears here was presented in a conference paper by Chamaret & O’Connor (2005); a slightly abridged version of the checklist is also found in Falck (ed., 2006, pp.48-49). A French translation, substantively similar to that given here, can be found in Faucheux & O’Connor (2015).

RADIOACTIVITY STEWARDSHIP ETHICAL BOTTOM LINES

- PR.1 Have the responsibilities of existing parties been appropriately assigned? For example:**
 - ◆ Application of a principle of national autonomy/responsibility ('take care of your own wastes' at national scale)?
 - ◆ Application of the principle that 'the polluter pays'?
 - ◆ Clear expression of, and respect for, local, national and international regulatory conditions?
- PR.2 Have responsibilities 'towards other parties' in the short term been adequately addressed? For example:**
 - ◆ Health security to workers and the public on or close to the site?
 - ◆ Security against attack in the face of external or internal sources of aggression?
- PR.3 Have responsibilities 'towards other parties' in the longer term been adequately addressed? For example:**
 - ◆ A 'sustainability' principle of inter-generational responsibility (don't pass on problems to others that you cannot cope with yourself)?
 - ◆ A thorough characterisation of risks/uncertainties/future contingencies (with reference to: the dangerous substances, the engineering works, the living environment, and future societal evolutions)?
 - ◆ An application of some version of the principle of precaution?
 - ◆ Is there likely long term stability of the necessary knowledge base (e.g., transmission of records, specialised know-how, local knowledge) for competent stewardship?
- PR.4 Has available technical knowhow and systems science been mobilised? For example:**
 - ◆ Rigorous profiling (in technical, medical and sociological terms) of the exposure risks?
 - ◆ Standards of best practice (technical reliability, simplicity...)?
 - ◆ Monitoring procedures attentive to a full spectrum of identified risks/uncertainties/future contingencies?
- PR.5 Is the solution economically viable? For example:**
 - ◆ Are the immediate costs of stewardship affordable with the available resources?
 - ◆ Clear picture of the trade-offs and relationship between clean-up and stewardship?
 - ◆ Are the solutions cost-effective for the identified risk reduction results?
 - ◆ Are there major financial costs shifted into the future?
 - ◆ Reasonable prospects of mobilising resources for the forecast stewardship costs in the longer term?
- PR.6 Does the solution enhance the prestige of the host communities and other stakeholder groups closely associated with the residual/waste site? For example:**
 - ◆ Viable partnership between local and national stakeholders (e.g., agreed distribution of responsibilities; legal mandate for stewardship activity; agreement on bases for financing of different cost components, etc.)?
 - ◆ Site specificities clearly in evidence?
 - ◆ Local competencies clearly in evidence?
 - ◆ Well defined framework for ongoing involvement of stakeholders in stewardship oversight and review?
 - ◆ Links to educational and training activities at local and wider scales?

APPENDIX E

Les ‘Fiches Marines de l’IRSN

L’objectif des **Fiches Marines** est de représenter, à l’aide des cartes, un ensemble d’actifs — économiques, sociétaux, environnementaux — pour des territoires considérés comme directement vulnérables dans le cas d’un accident majeur d’une installation nucléaire.

Pendant 2018-2019, un rapport a été établi sur la **méthodologie pour la mise en place de Fiches (Rapport n°RT/PSE-ENV/2018-00063)**, synthétisant, pour une zone géographique donnée du domaine marin, les caractéristiques environnementales, sa sensibilité et les enjeux qu’elle présente.

- **IRSN (20178), Mise en place des fiches descriptives des caractéristiques et des enjeux dans le domaine marin des installations nucléaires françaises. Fiches marines – Méthodologie. Rapport n°RT/PSE-ENV/2018-00063, Pôle Santé et Environnement**, Service de recherche sur les transferts et les effets des radionucléides sur les écosystèmes, IRSN, 19pp.

Depuis 2019, cette méthodologie a été envisagée pour chaque zone du littoral français considérée comme pouvant être soumise à un aléa nucléaire : à savoir, les embouchures des fleuves ayant sur leurs rives des installations du cycle du combustible, les zones proches des centrales nucléaires côtières et les ports militaires.

Une première Fiche Marine a été produite pendant 2020 pour **La Rade de TOULON**.

- **Fiche Marine – Rade de Toulon**, IRSN, 13pp.

Le travail de l’IRSN, interrompu par les complications sanitaires pendant 2020, a été repris, avec une première version de la Fiche Marine pour **Le COTENTIN** en avril 2021.

- LOUIS Louana, Céline DUFFA & Olivier RADAKOVITCH (2021), **Fiche Marine COTENTIN (Cherbourg – La Hague – Flamanville)** document de travail, IRSN, 20pp.

Cette fiche est suivie rapidement, en juin 2021, par une fiche analogue pour **La Rade de Brest**.

- LOUIS Louana, Céline DUFFA & Olivier RADAKOVITCH (2021), **Fiche Marine RADE DE BREST**, document de travail, IRSN, 24pp.

Une présentation synthétique de la méthodologie se trouve ensuite dans le rapport de stage par Louna LOUIS:

- LOUIS, Louna (2021), **Etude et Cartographie de la Vulnérabilité des Zones Côtières Françaises vis-à-vis de Contaminations Radioactives Accidentelles**, Rapport de Stage Master M1 SOAC-EE, Université Toulouse III Paul Sabatier & IRSN, Août 2021, 64pp.

Ce rapport de stage contient la Fiche Marine pour Brest comme son Annexe 3.

Ce même rapport de stage (sur sa page 10) affirme l’application de cette démarche également pour « les embouchures du Petit- et du Grand-Rhône, sorties du Rhône le long duquel fonctionnent les 4 centrales nucléaires de Bugey, Cruas, Saint-Alban et Tricastin ainsi que les installations de traitement de matière nucléaire du site de Marcoule ». Nous n’avons cependant pas pu consulter cette dernière Fiche Marine ; le traitement du cas des embouchures du Rhône dans le rapport de stage se limite essentiellement à l’analyse de vulnérabilité).

Les Fiches Marines sont donc des Cartes de Vulnérabilités qui inventorient les ressources et les activités physiques, économiques et écologiques sur chacune des 11 Zones Marines identifiées comme vulnérables.

LES CATEGORIES D’ACTIFS REPERTORIES SONT :

- Les zones d’estuaires des fleuves comportant des installations nucléaires etc.
- Caractéristiques physiques – géologie, bathymétrie courants marins marée etc.
- Caractéristiques et enjeux économiques et sanitaires
- Zones plages baignade plongée
- Pêche et aquaculture prises d’eau industrie et thalasso
- Sel marin
- Ports de plaisance ou de commerce
- Caractéristiques et richesses écologiques (marines et côtières).
- Biocénoses Zones Protégés, etc.

APPENDIX F

MONETARY EVALUATIONS OF ECOSYSTEM SERVICES AT RISK

Source : RAMIREZ, Felipe (2022), « *Intégration des ressources forestières et aquatiques dans l'analyse des conséquences économiques d'un accident nucléaire* ».

Présentation PPTx pour le Séminaire AMORAD-II, 21 mars 2022, IRSN.

OBJECTIF : ÉVALUER LES PERTES DE VALEURS ECONOMIQUES DIRECTEMENT ASSOCIEES A LA CONTAMINATION D'UN TERRITOIRE

- Valeur sur le marché de tous les biens et services produits sur le territoire (ex : valeur des denrées alimentaires, valeur des biens immobiliers, etc.)
- Tous les autres bénéfices pour la société qui n'ont pas un prix de marché (exemples : cueillette, qualité de l'air, etc.)

Composantes de coût de l'accident nucléaire déjà modélisées dans ARPAGON

- ❖ Effets sanitaires
- ❖ Pertes valeurs marchandes (entreprises + immobilier)
- ❖ Pertes agricoles
- ❖ Coût de relogement
- ❖ Effets de la décontamination

Composantes ajoutées par AMORAD-II dans ARPAGON

- ❖ Pertes bois brut
- ❖ Pertes pêche maritime

Composantes complémentaires adressés par AMORAD-II hors ARPAGON

- ❖ *Pertes de services écosystémiques associés à la chasse et la cueillette*
- ❖ *Pertes associées à des restrictions sur l'approvisionnement en eau potable*

EXEMPLE : COUTS POUR LE SECTEUR DE L'AGRICULTURE (BASSIN VERSANT DE LA LOIRE)

Valeur monétaire des pertes agricoles associées à la contamination des denrées produites sur les territoires contaminés.

Données d'entrée :

- Production (Agreste, Eurostat)
- Valeur de la production (INSEE, Agreste, Eurostat)
- Dépôts surfaciques après la fin d'accident (C3X)
- Facteurs de transfert de la contamination vers les denrées alimentaires (SYMBIOSE)
- Niveaux Maximums Admissibles (Euratom)

Pertes agricoles en Millions EUR actualisées sur 20 ans après l'accident :

- Avec remédiation de la contamination : 225,74 M€
- Sans remédiation de la contamination : 307,32 M€