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Astrolabes for the Anthropocene? Navigating deeply uncertain climate futures with lodestars of legal principle and decision making under deep uncertainty

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ABSTRACT
The Anthropocene is characterised by deeply entangled sociotechnical and natural regulatory processes. This article investigates entanglements between law and technology in the form of exploratory computer modelling tools, with various applications in anticipatory governance. After taking some bearings in the modern sociotechnical landscape, the tools and techniques of the Decision Making under Deep Uncertainty (DMDU) community of practice are presented as promising alternatives to existing methods. Despite their increasing use, DMDU methods appear undertheorised by legal scholars. This article therefore explores how legal principles could be integrated with DMDU in a novel conceptual framework. Extending a common navigational metaphor, it aims to theorise 'astrolabes for the Anthropocene' by reinventing widely recognised 'lodestars' of principle within existing anticipatory governance frameworks. The article concludes with a discussion of some perils and promises of integrated 'law-and-DMDU' and identifies areas for further debate between legal and DMDU scholars.

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KEYWORDS Decision making; deep uncertainty; anticipatory governance; climate change; the Anthropocene

1. Introduction

What actions can be taken to address climate change or other environmental challenges? What will the Nation's health-care system look like in the coming decades? Or the financial or transportation systems? What rules are going to constrain the development of A.I.?[1]

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[1]*Loper Bright Enterprises v Raimondo* 603 US ____ (2024) 1, 32 (Kagan J, dissenting).

Modern governance has long grappled with the challenge of regulating emerging technologies.[2] Part of the problem is that neither technological revolutions,[3] nor the governance frameworks that seek to regulate emerging technologies arrive fully formed.[4] As socially entangled processes, technology and governance could combine and develop along any of many different trajectories.[5] This social dimension is apparent in the competing goals and guiding principles of emerging technology governance, which strives for stability yet flexibility; to be historically rooted yet anticipatory and regulatory yet faciliatory.[6] In essence, the law- and policy-making challenge is to anticipate the future,[7] based on the sociotechnical landscape and information available in the present or recent past.[8]

There is clearly also a temporal dimension to the challenge. Governance frameworks could be newly devised or adapted from what currently exists, but all assume a particular sociotechnical state of affairs, somehow rooted in principle or experience.[9] Any of these conditions are liable to change. Yet nuances in entangled processes of sociotechnical change are often collapsed into a simplistic 'race' analogy, where governance and law must 'catch up' with technology.[10] This is problematic for a number of reasons,[11] not least the connotation of technological progress and reification of both 'technology' and 'law'.[12]

Moreover, there is also a dimension of profound uncertainty and indeterminacy inherent in emerging technology governance.[13] This reflects the profoundly *dis*equilibrating effects of modern technological development and reversal of the traditional relationship between means and ends; the means

[2]Hans Jonas, 'Toward a Philosophy of Technology' (1979) 9(1) *The Hastings Center Report* 34; Steven W Popper, 'Technological Change and the Challenges for 21st Century Governance' in Albert H Teich and others (eds), *AAAS Science and Technology Policy Yearbook 2003* (AAAS 2003); Diana M Bowman, Elen Stokes and Arie Rip (eds), *Embedding New Technologies into Society* (Jenny Stanford Publishing 2017); Stefan Aykut, David Demortain and Bilel Benbouzid, 'The Politics of Anticipatory Expertise: Plurality and Contestation of Futures Knowledge in Governance – Introduction to the Special Issue' (2019) 32(4) *Science & Technology Studies* 2.

[3]James H Moor, 'Why We Need Better Ethics for Emerging Technologies' (2005) 7(3) *Ethics and Information Technology* 111, 112.

[4]Elen Stokes, 'Review of *Environmental Principles and the Evolution of Environmental Law,* by Eloise Scotford' (2018) 81(5) *The Modern Law Review* 920, 921–922; Michael C Leach, 'Seeking "Systems" in Earth System Law: Boundaries, Identity, and Purpose in an Emergent Field' (2023) 15 *Earth System Governance* 100162.

[5]Diana M Bowman, Arie Rip and Elen Stokes, 'Introduction' in Diana M Bowman, Elen Stokes and Arie Rip (eds), *Embedding New Technologies into Society* (Jenny Stanford Publishing 2017) 3.

[6]Lyria Bennett Moses, 'Agents of Change: How the Law "Copes" with Technological Change' (2011) 20(4) *Griffith Law Review* 763, 767, 787; Bowman, Rip and Stokes (n 5) 3.

[7]Aykut, Demortain and Benbouzid (n 2).

[8]Bennett Moses (n 6); Aykut, Demortain and Benbouzid (n 2).

[9]Bennett Moses (n 6) 768–770; Vincent F Ialenti, 'Adjudicating Deep Time: Revisiting the United States' High-level Nuclear Waste Repository Project at Yucca Mountain' (2014) 27(2) *Science & Technology Studies* 27; Bowman, Rip and Stokes (n 5) 3.

[10]Lyria Bennett Moses, 'Recurring Dilemmas: The Law's Race to Keep Up with Technological Change' (2007) 2007(2) *Journal of Law, Technology & Policy* 239; Bowman, Rip and Stokes (n 5) 6.

[11]Bennett Moses (n 6) 763–766.

[12]Bennett Moses (n 10) 242.

[13]Bowman, Rip and Stokes (n 5) 3–5.

of technological progress becomes the end in itself, while the ends are ever changing.[14] Emerging technology trajectories are therefore multidirectional and deeply uncertain.[15] Such uncertainty is often analysed using navigational metaphors.[16] For all these reasons, this article uses the metaphor of the astrolabe. Here the astrolabe represents a novel conceptual framework for governing emerging technologies of exploratory computer modelling with various potential applications across public law and policy. In this conceptualisation, the computer modelling (knowledge production) part of the entanglement serves as 'cartographer', while the law, policy and public participation (governance) part of the entanglement serves as 'navigator'.[17] As such, these particular computer modelling tools do not aim to supplant deliberation and decision-making, nor 'close down' the future, but rather to offer a 'prosthesis' for exploring alternative futures.[18]

This Special Issue discusses profound entanglements in social, technological, and natural regulatory processes in the Anthropocene.[19] In this article, I will consider entanglements in the 'sociotechnical infrastructures'[20] of anticipation in modern law- and policy-making, in the context of the Anthropocene and its inherent uncertainty. These entanglements involve 'technology' in multiple senses. The computer model, including its algorithms and outputs, is a core and 'in many ways indispensable' tool in anticipatory law and governance.[21] But the entanglements extend far beyond these tools alone. In many jurisdictions, sociotechnical infrastructures of anticipation also include broader knowledge production processes and social practices. For example, experts assemble, debate and contest their ideas and methods, and build relationships with

[14]Jonas (n 2) 13.

[15]Sven O Hansson and Gertrude Hirsch Hadorn, 'Introducing the Argumentative Turn in Policy Analysis' in Sven O Hansson and Gertrude Hirsch Hadorn (eds), *The Argumentative Turn in Policy Analysis: Reasoning about Uncertainty* (Springer 2016) 18–20.

[16]eg, Blaise Pascal and T S Eliot, *Pascal's Pensées* (EP Dutton 1958) 20, Pensée 72 ('sailing within a vast sphere, ever drifting in uncertainty'); Armin Grunwald, 'The Hermeneutic Perspective on Modeling in Technology Assessment' in Armin Grunwald, Alfred Nordmann and Martin Sand (eds), *Hermeneutics, History, and Technology: The Call of the Future* (History and philosophy of technoscience vol 24. Routledge Taylor & Francis Group 2023) (referring to researchers as 'mapmakers' and public policymakers as 'navigators'); Ian Scoones, *Navigating Uncertainty: Radical Rethinking for a Turbulent World* (Polity 2024).

[17]Ottmar Edenhofer and Martin Kowarsch, 'Cartography of Pathways: A New Model for Environmental Policy Assessments' (2015) *51 Environmental Science & Policy* 56, 63; Grunwald (n 16) 188.

[18]Robert J Lempert, Steven W Popper and Steven C Bankes, *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-term Policy Analysis* (RAND Corporation 2003) xii–xiv; Paul Raskin, 'Which Future Are We Living In? Opening Essay for a GTI Forum' (2022) <https://greattransition.org/gti-forum/which-future-raskin> accessed 3 January 2024.

[19]For consistency across the Special Issue, the term 'Anthropocene' is used throughout, while acknowledging strong critiques and alternative concepts: Andreas Malm and Alf Hornborg, 'The Geology of Mankind? A Critique of the Anthropocene narrative' (2014) 1(1) *The Anthropocene Review* 62; Oliver López-Corona and Gustavo Magallanes-Guijón, 'It Is Not an Anthropocene; It Is Really the Technocene: Names Matter in Decision Making under Planetary Crisis' (2020) 8 *Frontiers in Ecology and Evolution*.

[20]Aykut, Demortain and Benbouzid (n 2).

[21]Ibid 9.

policymakers.[22] These sociotechnical dynamics have also become entangled with law, since at least the emergence of environmental impact assessments[23] and regulatory impact assessments (RIAs) in the United States.[24] RIAs are routinely required by various rules, orders or 'one-in-one-out' policies.[25] For example, US Executive Orders require cost-benefit analysis of proposed administrative rule-making,[26] while fundamental rights impact assessments are required under the European Union regulations on data protection and artificial intelligence.[27] RIAs, often using computer modelling tools, are now so entrenched that they even serve as gatekeepers to the legislative process; the European Commission's 'Better Regulation' rules require an RIA of new *legislative* proposals.[28] In these ways, RIAs represent technology that is not only regulated by laws, but technology that has come to regulate the law itself. Thus, RIAs tell a familiar story of inseparable technological, social and political relations, technological lock-in, and path dependence.[29]

In the context of this Special Issue, the sociotechnical entanglements I am describing represent both regulation *of* technology and regulation *by* technology.[30] Yet the particular modelling tools and practices introduced and considered below remain undertheorised in law and governance scholarship, whether in general[31] or in the context of the Anthropocene.[32] Moreover, these tools and techniques are maturing at an opportune moment, in light of recent legal developments such as the *Loper Bright Enterprises*[33] decision

[22]Ibid 7–8.

[23]Alina Wernick, 'Impact Assessment as a Legal Design Pattern – A "Timeless Way" of Managing Future Risks?' (2024) 3(2) *Digital Society* 5.

[24]James R Drummond and Claudio M Radaelli, 'Behavioural Analysis and Regulatory Impact Assessment' (2024) 15(4) *European Journal of Risk Regulation* 950.

[25]OECD (2023) 'Government at a Glance 2023' 100, 102.

[26]See, e.g. Exec Order No 12291, Federal Regulation, 46 FR 13193 (19 February 1981); Exec Order 12866, Regulatory Planning and Review, 58 FR 51735 (4 October 1993); Exec Order No 13563, Improving Regulation and Regulatory Review, 76 *FR* 3821 (21 January 2011).

[27]Wernick (n 23).

[28]European Union, 'Interinstitutional Agreement between the European Parliament, the Council of the European Union and the European Commission on Better Law-Making: Interinstitutional Agreement of 13 April 2016 on Better Law-Making' (2016); European Commission, 'Better Regulation: Guidelines and Toolbox' (July 2023) <https://commission.europa.eu/law/law-making-process/planning-and-proposing-law/better-regulation/better-regulation-guidelines-and-toolbox_en> accessed 9 September 2023.

[29]Bowman, Rip and Stokes (n 5) 4.

[30]Popper (n 2) 98.

[31]Cf Daniel A Farber, 'Modeling Climate Change and Its Impacts: Law, Policy, and Science' (2008) 86(7) *Texas Law Review* 1655; Cass R Sunstein, *Worst-Case Scenarios* (Harvard University Press 2009); David Weisbach, 'Developing Regulatory Policy in the Context of Deep Uncertainty: Legal, Economic, and Natural Science Perspectives [Special Issue]' (2015) 44(S2) *The Journal of Legal Studies*.

[32]Cf John S Dryzek and Hayley Stevenson, 'Global Democracy and Earth System Governance' (2011) 70(11) *Ecological Economics* 1865; Olivia Woolley, *Ecological Governance: Reappraising Law's Role in Protecting Ecosystem Functionality* (Cambridge University Press 2014); John S Dryzek, 'Institutions for the Anthropocene: Governance in a Changing Earth System' (2016) 46(4) *British Journal of Political Science* 937; John S Dryzek and Jonathan Pickering, 'Deliberation as a Catalyst for Reflexive Environmental Governance' (2017) 131 *Ecological Economics* 353.

[33]*Loper Bright Enterprises v Raimondo* (n 1).

of the US Supreme Court and the passage of (and backlash to) the European Green New Deal. But what are these tools and techniques?

In the last two decades, significant advances in computer technology enabled the development of new exploratory modelling techniques and 'decision support' tools.[34] An increasingly influential subset of these tools and techniques has converged in the community of practice known as Decision Making under Deep Uncertainty (DMDU).[35] The community operates in various fields of great public interest,[36] but especially in climate change policy.[37] DMDU methods assume 'good' decisions can be made without reliable predictions, through systematic, deliberative and iterative analysis of policy options.[38] In general, most DMDU methods:

(1) begin from the 'back end' with clear formulation of the policy question, rather than seek to determine an 'optimal' policy;[39]
(2) clearly characterise uncertainties and, rather than agree about assumptions, carry multiple sets of (potentially contradictory) assumptions through the whole analysis;
(3) analyse multiple criteria, including differences in policy options, instruments, model design, causal relationships and performance metrics, 'opening up' available futures;[40]
(4) include stakeholders in developing and running the analyses iteratively over time; and
(5) preserve the accessibility and transparency of more detailed information leading to the ultimate analytical outputs, allowing decision-makers to 'drill down', if desired.[41]

[34] Lempert, Popper and Bankes (n 18).
[35] Vincent A W J Marchau and others (eds), *Decision Making under Deep Uncertainty* (Springer International Publishing 2019).
[36] Robert J Lempert, 'Robust Decision Making (RDM)' in Vincent A W J Marchau and others (eds), *Decision Making under Deep Uncertainty* (Springer International Publishing 2019); Muriel C B Stanton and Katy Roelich, 'Decision Making under Deep Uncertainties: A Review of the Applicability of Methods in Practice' (2021) 171 *Technological Forecasting and Social Change* 120939.
[37] Farber (n 31), 1691–1692; Sara M Constantino and Elke U Weber, 'Decision-making under the Deep Uncertainty of Climate Change: The Psychological and Political Agency of Narratives' (2021) 42 *Current Opinion in Psychology* 151; Diana Reckien, Cathy Vaughan and Rachael Shwom, 'Climate Decision-making [Special Issue]' (2021) 51–52 *Current Opinion in Environmental Sustainability*; Mark New and others, 'Decision-making Options for Managing Risk' in Intergovernmental Panel on Climate Change (IPCC) (ed), *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2023); David A Stainforth, *Predicting Our Climate Future: What We Know, What We Don't Know, and What We Can't Know* (Oxford University Press 2023) ch 21, 239–240; Robert J Lempert and others, 'The Use of Decision Making under Deep Uncertainty in the IPCC' (2024) 6 *Frontiers in Climate*.
[38] Lempert, Popper and Bankes (n 18) iii; Marchau and others (eds) (n 35) 4.
[39] Lempert, Popper and Bankes (n 18) 127.
[40] Ibid 60, 143; Andy Stirling, '"Opening Up" and "Closing Down": Power, Participation, and Pluralism in the Social Appraisal of Technology' (2008) 33(2) *Science, Technology, & Human Values* 262.
[41] Steven W Popper, 'Reflections: DMDU and Public Policy for Uncertain Times' in Vincent A W J Marchau and others (eds), *Decision Making under Deep Uncertainty* (Springer International Publishing 2019) 385–389.

DMDU methods offer an alternative to predictive, 'optimal' analyses. The general approach is consistent with calls for 'wiser' use of computer technology,[42] technological humility,[43] and emerging norms of law and governance in the Anthropocene.[44] However, while the concept of 'deep uncertainty' and the DMDU community are now well-established, they remain understudied by legal scholars.[45] This article addresses that gap. It aims to establish direct links between the DMDU community and legal scholars, using theoretical concepts from each field to promote mutual translation. Such translations are necessary because of a pervasive 'two cultures' problem.[46] This is manifest in a common trend of mutual illiteracy, where 'law' often treats 'technology' as a black box, and vice versa.[47] Here, legal scholarship and DMDU literature pass each other like proverbial ships in the night. At the same time, enhanced understanding of DMDU offers legal scholars the opportunity to improve their 'futures literacy'.[48] For all these reasons, this article aims to address this cultural divide and promote mutual understanding between these two previously parallel fields. Such a translation appears timely and necessary in anticipation of future litigation challenging the scope and/or outputs of DMDU analyses in particularly contentious policy-making.[49] Further and in any event, lawyers and judges will at some stage need to grapple with what DMDU is, how it works and its implications for law, just as they are often called upon to resolve legal dilemmas and uncertainties caused by new technologies.[50] This is because DMDU represents a computer-assisted change in our collective knowledge and understanding about how to deal with uncertainty; it signifies a discontinuity in the sociotechnical landscape of anticipation.[51] In these ways, the future

[42]Jonas (n 2) 23; Stephen Toulmin, *Return to Reason* (Harvard University Press 2001) 80–82.

[43]Hans Jonas, *The Imperative of Responsibility: In Search of an Ethics for the Technological Age* (University of Chicago Press 1984) 22; Sheila Jasanoff, 'Technologies of Humility' (2007) 450(7166) *Nature* 33.

[44]Xuemei Bai and others, 'Plausible and Desirable Futures in the Anthropocene: A New Research Agenda' (2016) 39 *Global Environmental Change* 351; Dryzek (n 32); Dryzek and Pickering (n 32); Geoffrey Garver, *Ecological Law and the Planetary Crisis: A Legal Guide for Harmony on Earth* (Routledge Taylor & Francis Group 2021) ch 11.

[45]Farber (n 31) 1691–1692, recognised the potential of Robust Decision-Making, a paradigmatic DMDU method, yet only considered it briefly; Meanwhile, law-and-economics contributions do not explicitly address the DMDU community of practice: Sunstein (n 31); Weisbach (n 31).

[46]Jens Beckert and Richard Bronk, 'An Introduction to Uncertain Futures' in Jens Beckert and Richard Bronk (eds), *Uncertain Futures: Imaginaries, Narratives, and Calculation in the Economy* (1st edn, Oxford University Press 2018) 5; Popper (n 41) 384–385.

[47]Bennett Moses (n 6) 774–775, 786.

[48]Elen Stokes, 'Wanted: Professors of Foresight in Environmental Law!' (2019) 31(1) *Journal of Environmental Law* 175; Elen Stokes and Ben Pontin, 'Historical Futures and Future Futures in Environmental Law Pedagogy: Exploring "Futures Literacy"' (2022) 18(4) *International Journal of Law in Context* 440.

[49]eg, the 'Colorado River Basin Post-2026 Operations Exploration Tool' is a DMDU tool currently used by the US Bureau of Reclamation to guide its 'Post-2026 Process' and Environmental Impact Statement (EIS) under the National Environmental Policy Act (NEPA): Martin & McCoy LLC dba Virga Labs, 'Colorado River Basin Post-2026 Operations Exploration Tool' (2024) <https://www.crbpost2026dmdu.org/>.

[50]Bennett Moses (n 10) 239–240; Bennett Moses (n 6) 784–785.

[51]Bennett Moses (n 6) 766–770.

'technological trajectory' of DMDU will be shaped by its encounters with law, whether by litigation,[52] regulation,[53] or in some other as yet unforeseen way.

The mutual translation exercise is structured in this article as follows. First, we must take our bearings in the existing sociotechnical landscape, including our understanding of technology, what problems DMDU aims to address and where it fits in anticipatory Anthropocene governance. Then we will consider the iterative cycle typical of most DMDU analyses. In the next step, we will explore the contours of anticipatory governance by integrated 'law-and-DMDU' devices, or possible 'astrolabes for the Anthropocene'. This article argues that navigation would be enabled by four plausible 'lodestars' of widely recognised principle: rationality, relevance, robustness, and reasonableness. These principles will be used to translate between legal and DMDU theory to establish an integrated conceptual framework for law-and-DMDU. This conceptualisation is shown in Figure 1.

The interpretive, translative approach is inspired by a longstanding academic practice, whereby old concepts are reinvented to serve new purposes in new contexts, particularly in response to new technologies.[54] Having sketched the outlines of one possible conceptual framework for law-and-DMDU, we will proceed to discuss some basic limitations and practical barriers to further integration in future.

2. Taking our bearings

2.1. On technology

Technology is a slippery concept, ranging from a specific tool, to an abstract noun, to various other meanings depending on context.[55] Meanings further proliferate across disciplines.[56] It is therefore important to specify what is meant by 'technology' here.

A dictionary suggests the ordinary meaning of technology is the study, practical application or product of the mechanical arts and applied sciences.[57] This includes both a tool per se, but also the social knowledge and practices surrounding any tool. Sociotechnical entangledness is

[52]Sheila Jasanoff, *Science at the Bar* (Harvard University Press 1997) 12; Bennett Moses (n 6) 784–785.
[53]Bowman, Stokes and Rip (eds) (n 2).
[54]Toulmin (n 42); Ialenti (n 9) 36–40.
[55]Thomas P Hughes, *Human-Built World: How to Think about Technology and Culture* (University of Chicago Press 2005) 2–5, 175–177; Bennett Moses (n 10) 243–247.
[56]Bennett Moses (n 10) 243–247.
[57]'technology, n' (*OED Online*, OUP December 2023) <https://doi.org/10.1093/OED/8192265936> accessed 27 August 2024.

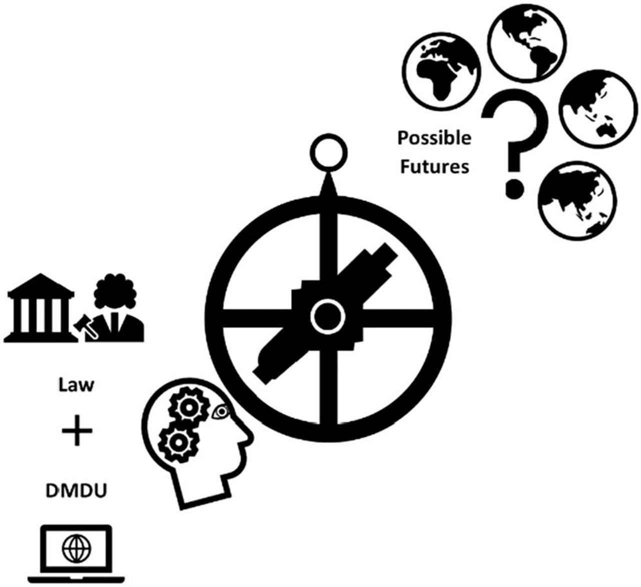

Figure 1. The basic conceptual framework for this article, in which law combines with decision making under deep uncertainty (DMDU) to help decide between alternative possible futures in the Anthropocene. (Visualisation by author).

therefore elemental.[58] However, in a now obsolete sense, a technology was also a systematic treatise on a topic, comparable to an encyclopedia or a dictionary.[59] Both meanings underline the human *usefulness* of technology. Thus, as a working definition, let us assume that technology is: ' any tool or technique, any product or process, any physical equipment or method of doing or making, by which human capability is extended.'[60]

DMDU is technology in the following senses. First and foremost, DMDU consists of computer-based exploratory modelling tools and particular practices carried out with these tools.[61] It is therefore technology in the modern sense. However, DMDU is also technology in the obsolete sense because these tools and practices systematically generate exceedingly large numbers of alternative futures in the particular circumstances of a real-world, multi-criteria decision-making process.[62] These futures are compiled in the form of complex computer code and graphics far removed from a written treatise. Nevertheless, this ' representation pulls the phenomena together in a way

[58]Harro van Lente and Arie Rip, 'Reflexive Co-Evolution and Governance Patterns' in Diana M Bowman, Elen Stokes and Arie Rip (eds), *Embedding New Technologies into Society* (Jenny Stanford Publishing 2017) 19.
[59]'technology, n' (n 57).
[60]Donald A Schon, *Technology and Change* (Dell Publishing 1967) 1
[61]Marchau and others (eds) (n 35).
[62]Lempert, Popper and Bankes (n 18).

that makes intelligible sense, giving a systematic grasp of the field concerned'.[63] Thus, the DMDU community sees itself as offering a 'prosthesis', extending the human capability for systematically imagining alternative futures despite deep uncertainty.[64]

Law can also be considered a technology.[65] This is most obvious in particular legal devices such as regulatory 'instruments', or legal 'fictions' and 'inventions',[66] but can also be conceived more broadly on sociotechnical or systemic scales.[67] Law shapes, is shaped by and reflexively interacts with sociotechnical change.[68] Amid this dynamism, sociotechnical change might be said to open up what *can* be done, while legal change is interested in what *may* be done.[69] This distinction accounts for the notion of law 'lagging behind' sociotechnical change, but it is not determinative; law independently has a role in extending what is considered possible.[70] Nevertheless, this distinction gives rise to various regulatory problems, such as the 'Collingridge Dilemma'. As new technological innovations emerge, regulators lack the ability to accurately predict the technology's ultimate effects and thus the appropriate regulatory burden (i.e. law could out-manoeuvre technology). Yet, once the technology becomes established, regulators may be stymied by power and vested interests entrenched by the technology's intervening development (i.e. technology may out-manoeuvre law).[71] Finally, in this context it is important to note a possible circularity in integrating 'law-and-DMDU'. Given the entrenchment of modelling and RIA in modern law-making, DMDU represents an emerging technology that could itself extend relevant regulatory capability.[72]

While much more could be said about technology and law, this discussion suffices to draw the following preliminary conclusions. DMDU is technology in at least two senses. Law is also a technology, but it is neither merely reactive to, nor is it determined by sociotechnical change.[73] Further, we must not

[63]Toulmin (n 42) 173.
[64]Lempert, Popper and Bankes (n 18) xii–xiv; Raskin (n 18).
[65]Mario Biagioli and Marius Buning, 'Technologies of the Law/Law as a Technology' (2019) 57(1) *History of Science* 3, 16–17; Garver (n 44) ch 4; Jorge E Viñuales, 'Comparing Environmental Law Systems' (2024) 73(1) *ICLQ* 247, 250, 258.
[66]Gunther Teubner, 'Rights of Non-humans? Electronic Agents and Animals as New Actors in Politics and Law' (2006) 33(4) *Journal of Law and Society* 497, 514–515, 521; Bennett Moses (n 10) 246–247; *Loper Bright Enterprises v Raimondo* (n 1), agreeing legal presumptions are 'fictional' (majority 29; Gorsuch J 13, concurring; Kagan J 15, 30, dissenting), but disagreeing on constitutional appropriateness of 'inventions'.
[67]Garver (n 44) ch 4; Viñuales (n 65).
[68]Bennett Moses (n 6) 766–770; Biagioli and Buning (n 65) 15–17.
[69]Bennett Moses (n 10) 245.
[70]Teubner (n 66), 501–502, 521; Karla Hoff and James Walsh, 'The Third Function of Law' in K Basu and R Hockett (eds), *Law, Economics, and Conflict* (Cornell University Press 2021).
[71]David Collingridge, *The Social Control of Technology* (St. Martin's Press 1980).
[72]Popper (n 2) 98; Bennett Moses (n 10) 246–247.
[73]Biagioli and Buning (n 65) 17; See also: Herbert L Hart, 'Discretion' (2013) 127(2) *Harvard Law Review* 652, 662 (Observing that we do not live in a world of 'mechanical Jurisprudence').

reify simple distinctions between DMDU and law, because both are entangled in modern sociotechnical infrastructures of anticipation.[74] Moreover, DMDU and law should be integrated because 'no technical procedure can guarantee its own humane or rational use'[75] and law should protect important social values.[76] This militates against either DMDU without law,[77] or law blind to decision-making innovations like DMDU.[78] With this in mind, let us now consider the kinds of mischief to which law-and-DMDU might be directed.

2.2. On deep uncertainty

'Deep uncertainty'[79] is defined as any situation where experts or stakeholders do not know or cannot agree on:

(1) appropriate conceptual models that describe relationships among drivers in a system;
(2) the probability distributions used to represent uncertainty about variables and parameters, and/or;
(3) how to weigh and value desirable alternative outcomes.[80]

Note that limbs (1) and (2) reflect epistemic uncertainty, whereas limb (3) reflects normative uncertainty. While this definition comes from computational modelling and typically involves quantification, the concept of 'deep uncertainty' is recognised in both physical and social science research.[81]

Deep uncertainty can also be conceptualised as a spectrum of the qualitative state of knowledge. This spectrum ranges from complete certainty (determinism) on one extreme, to total ignorance (indeterminacy) on the other, as

[74]Bennett Moses (n 10) 242–243; Aykut, Demortain and Benbouzid (n 2); Biagioli and Buning (n 65) 17.
[75]Toulmin (n 42) 78.
[76]Bennett Moses (n 10) 248–249; Bennett Moses (n 6) 767; Riikka Koulu, 'Crafting Digital Transparency: Implementing Legal Values into Algorithmic Design' (2021) 8(1) *Critical Analysis of Law* 81.
[77]Cathy O'Neil, *Weapons of Math Destruction: How Big Data Increases Inequality and Threatens Democracy* (1st edn, Crown 2016); Emre Bayamlıoğlu and Ronald Leenes, 'The "Rule of Law" Implications of Data-driven Decision-making: A Techno-regulatory Perspective' (2018) 10(2) *Law, Innovation and Technology* 295.
[78]Albert W Alschuler, *Law Without Values: The Life, Work, and Legacy of Justice Holmes* (University of Chicago Press 2000); Toulmin (n 42) 80.
[79]Note the overlap with various similar, yet distinguishable concepts of uncertainty: Hansson and Hirsch Hadorn (n 15) 18–21 (on 'great', 'deep' and 'radical' uncertainty); On the distinction between 'uncertainty' and other concepts, see: Frank H Knight, *Risk, Uncertainty and Profit* (The Riverside Press Cambridge 1921); J M Keynes, 'The General Theory of Employment' (1937) 51(2) *The Quarterly Journal of Economics* 209; Stirling (n 40).
[80]New and others (n 37) 2578. See also Lempert, Popper and Bankes (n 18); Marchau and others (eds) (n 35).
[81]Anita Engels and others, 'Hamburg Climate Futures Outlook: The plausibility of a 1.5°C Limit to Global Warming –– Social Drivers and Physical Processes' (2023) 20–22.

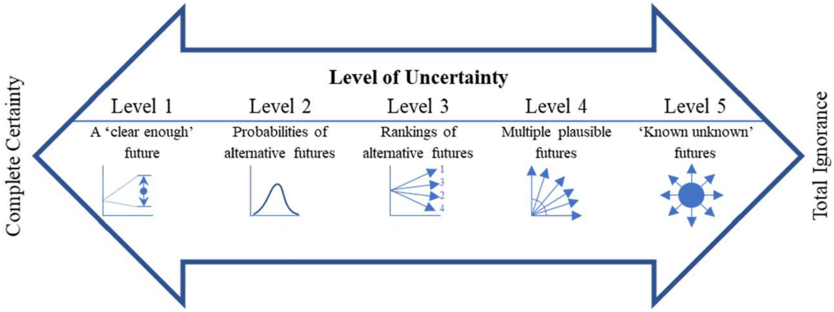

Figure 2. Deep uncertainty conceptualised as different levels along a spectrum of the qualitative state of knowledge relevant to a given decision. (Adapted from Marchau et al. 2019; Sillmann et al. 2021).

shown in Figure 2. Between these two extremes, the DMDU community identifies five levels of uncertainty.[82] Levels 1–3 are all relatively straightforward, with progressive increases in the complexity of variables, outcomes, weights and the overall future predictability of a system. Levels 4 and 5 represent 'deep uncertainty'.[83] The main difference is that Level 4 uncertainty represents irreducibly broad variability, whereas Level 5 uncertainty represents 'known unknown' variability.[84] DMDU methods are designed to assist policymakers with Levels 4 or 5.

The Anthropocene is riddled with deep uncertainty, manifest even in the profound scientific disagreement about recognition of any new geological epoch. Despite 'decisively' rejecting the Anthropocene Working Group's proposal,[85] the Sub-commission on Quaternary Stratigraphy acknowledged the 'wide body of data on human impacts on global systems'.[86] This chronostratigraphic controversy turns on conceptual disagreement about prevailing geological models and rival indicators of the 'Anthropocene'.[87] In other words, considered against the deep uncertainty definition above, the disagreement revolves around the conceptual first limb and the evaluative third limb. Many other large-scale deep uncertainties have been considered

[82]cf Warren E Walker, Robert J Lempert and Jan H Kwakkel, 'Deep Uncertainty' in Saul I Gass and Michael C Fu (eds), *Encyclopedia of Operations Research and Management Science* (Springer US 2013); Marchau and others (eds) (n 35); Jana Sillmann and others, 'Event-based Storylines to Address Climate Risk' (2021) 9(2) *Earth's Future*.

[83]Walker, Lempert and Kwakkel (n 82); Marchau and others (eds) (n 35) 8; Sillmann and others (n 82).

[84]See also Donald H Rumsfeld, *DoD News Briefing – Secretary Rumsfeld and Gen. Myers* (Federal News Service Inc. 2002).

[85]Colin Waters and others, *Executive Summary: The Anthropocene Epoch and Crawfordian Age: Proposals by the Anthropocene Working Group* (2024).

[86]International Union of Geological Sciences, 'The Anthropocene' (20 March 2024) <https://www.iugs.org/_files/ugd/f1fc07_40d1a7ed58de458c9f8f24de5e739663.pdf?index=true>.

[87]Ibid.

and debated in the context of the Anthropocene.[88] Given this Special Issue's focus on sociotechnical entanglements with the environment, the remainder of this article focuses on deep uncertainty in the context of climate change.

Climate change is paradigmatic of deep uncertainty,[89] but this is not to lend any credence to 'climate scepticism'. Climate science has established a 'chain of robust understanding'[90] that accounts for serious threats posed to the Earth System, including particular confidence in collective knowledge about the enhanced greenhouse effect.[91] Rather, to say that climate change is 'deeply uncertain' is to say that it remains very difficult to apply this robust knowledge to inform climate-related public policymaking.[92] The uncertainty comes from various sources. A fundamental source is reliance on global climate models (GCMs), an essential technology in climate science. This is so for good reason: we only have one Earth, with one climate system. We therefore have a 'one-shot-bet' in terms of the consequences of our decisions in the present on the future trajectory of Earth's climate.[93] Yet because Earth's climate is a chaotic system, there are multiple possible paths the current climate could have emerged from in the past, just as there are multiple possible paths it could traverse in future.[94]

Since there is only one Earth and one climate system, yet multiple possible past and future trajectories, climate science relies on GCMs to experiment with simulated Earths. This proceeds from the assumption that the real Earth's climate system can be approximated by coupled non-linear chaotic system models.[95] GCMs operate on physical laws and principles of mathematical chaos, including initial condition sensitivity, non-linearity and emergence (the 'butterfly effect').[96] However, basic limits in human knowledge and computing power mean GCMs can only *approximate* real climate behaviour. Moreover, GCMs diverge in design and operation *inter se* because they were developed in different scientific cultures and they rely on user-defined inputs[97] as proxies for dynamic processes not replicated by physical laws.[98]

[88]cf Malm and Hornborg (n 19); Dipesh Chakrabarty, 'Anthropocene Time' (2018) 57(1) *History and Theory* 5, 30–31; López-Corona and Magallanes-Guijón (n 19).

[89]Marchau and others (eds) (n 35) ch 1.

[90]See, e.g., Stainforth (n 37) 51–57.

[91]Ibid 247–256.

[92]Marchau and others (eds) (n 35), 2–3; Sillmann and others (n 82); Reckien, Vaughan and Shwom (n 37); Constantino and Weber (n 37).

[93]Stainforth (n 37).

[94]Ibid; See also: Toulmin (n 42) ch 4.

[95]B. Moore and others, 'Advancing Our Understanding' in J T Houghton and others (eds), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2001).

[96]Erica Thompson, *Escape from Model Land: How Mathematical Models Can Lead Us Astray and What We Can Do About It* (Basic Books 2022); Stainforth (n 37).

[97]Known as 'parameterisations'.

[98]Thompson (n 96); Stainforth (n 37).

Climate model diversity should be a strength. However, GCMs are not completely independent[99] and so the extent of model 'outcome space' is mathematically uncertain.[100] Further, GCMs are biased by 'training' on historical data, because these represent just one of multiple possible paths that could have led to today's climate.[101] Exploration of these alternative paths could be another strength of GCMs. However, results generated for a simulated Earth are all too often transposed to the real Earth under social pressure to provide definitive answers.[102] Societies cannot expect such certainty from GCMs. This unavoidable deep uncertainty requires policymakers to 'embrace the vague' and deliberate on the basis of relative plausibility.[103]

In summary, climate futures in the Anthropocene are deeply uncertain. Despite robust understanding about human impacts on global systems, deep uncertainty perpetuates an old paradox: as the sphere of knowledge grows, its circumference of uncertain knowledge expands accordingly.[104] Thus, while physical climate science is robust and GCMs demonstrate considerable skill, we must beware the continuous practical relevance of deep uncertainty. Latent modelling uncertainties compound when GCM outputs are 'downscaled' to decision-relevant areas[105] and used to infer the 'likelihood' of climate events[106] or to estimate costs and benefits of alternative policies.[107] While model-based decision support seems inescapable in contemporary policymaking,[108] we must escape 'Model Land' in interpreting model outputs.[109] This poses critical challenges to traditional regulatory approaches premised on prediction,[110] uncertainty reduction[111] and the precautionary principle.[112]

[99]For example, model code is commonly shared between research institutions: Thompson (n 96); Stainforth (n 37).

[100]Wendy Parker, 'Climate Science' (2018) <https://plato.stanford.edu/entries/climate-science/> accessed 2 January 2024; David A Stainforth and others, 'Issues in the Interpretation of Climate Model Ensembles to Inform Decisions' (2007) 365(1857) *Philosophical Transactions Series A, Mathematical, Physical, and Engineering Sciences* 2163; Stainforth (n 37) ch 21.

[101]Naomi Oreskes, Kristin Shrader-Frechette, and Kenneth Belitz, 'Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences' (1994) 263(5147) *Science* 641; Stainforth (n 37) 183.

[102]Thompson (n 96); Stainforth (n 37).

[103]Stainforth (n 37) 273.

[104]Often attributed to Blaise Pascal: Pascal and Eliot (n 16) 16–17, 20, Pensée 72; but its origins are ironically also uncertain: Stuart Firestein, *Ignorance: How It Drives Science* (Oxford University Press 2012) 29.

[105]Stainforth (n 37) 90–91, 96, 163, 272–273.

[106]Parker (n 100); Stainforth (n 37) ch 19.

[107]Marchau and others (eds) (n 35) 3; Stainforth (n 37) ch 25.

[108]Aykut, Demortain and Benbouzid (n 2).

[109]Thompson (n 96).

[110]Stainforth (n 37).

[111]Joseph G Morone and Edward J Woodhouse, *Averting Catastrophe: Strategies for Regulating Risky Technologies* (University of California Press 1986).

[112]cf Jonathan Verschuuren, 'The Role of Sustainable Development and the Associated Principles of Environmental Law and Governance in the Anthropocene' in Louis J Kotzé (ed), *Environmental Law and Governance for the Anthropocene* (Hart Publishing 2017); Han Somsen, 'The End of European

2.3. On anticipatory governance in the Anthropocene

It is clear now that modern anticipatory governance is entangled in a sociotechnical environment.[113] The Anthropocene is this entanglement writ large. For example, climate change is melting Earth's polar icecaps, with measurable effects on planetary rotation, the length of the terrestrial day, and sensitive sociotechnical systems.[114] Such entanglements affect the nature of knowledge itself. The Anthropocene smashes many shibboleths of modernity. The environment is highly dynamic, not static.[115] Science is post-normal[116] and post-Cartesian.[117] Knowledge is contingent and value-laden,[118] and these values are in flux.[119]

All of this points to deep normative uncertainty, on top of the kind of deep epistemic uncertainty discussed earlier.[120] In short, humans have taken command of nature, without assuming control.[121] Scholarly responses differ on this aspect of uncertainty. Many lawyers adopt a systemic perspective and theorise new norms fit for the Anthropocene.[122] Yet, like any number of smaller scale sociotechnical 'revolutions',[123] the Anthropocene did not just happen 'by itself'.[124] It is precisely because of profound sociotechnical and environmental entanglements that entirely new legal theoretical or normative systems are implausible.[125] Some philosophers call for a return to practical wisdom;[126] but what counts as 'wisdom'[127] in a sociotechnical environment without analogue in human experience?[128] Atmospheric

Union Environmental Law: An Environmental Programme for the Anthropocene' in Louis J Kotzé (ed), *Environmental Law and Governance for the Anthropocene* (Hart Publishing 2017).

[113]Or 'ecotechnological environment': Hughes (n 55) ch 6.

[114]Mostafa K Shahvandi and others, 'Contributions of Core, Mantle and Climatological Processes to Earth's Polar Motion' (2024) 17(7) *Nature Geoscience* 705; Damian Carrington, 'Climate Crisis is Making Days Longer, Study Finds: Melting of Ice is Slowing Planet's Rotation and Could Disrupt Internet Traffic, Financial Transactions and GPS' (15 July 2024) <https://www.theguardian.com/environment/article/2024/jul/15/climate-crisis-making-days-longer-study> accessed 16 July 2024.

[115]Somsen (n 112) 367–369.

[116]Silvio O Funtowicz and Jerome R Ravetz, 'Science for the Post-normal Age' (1993) 25(7) *Futures* 739.

[117]Malm and Hornborg (n 19) 67, Note 1.

[118]Toulmin (n 42); Vito de Lucia, 'Critical Environmental Law and the Double Register of the Anthropocene: A Biopolitical Reading' in Louis J Kotzé (ed), *Environmental Law and Governance for the Anthropocene* (Hart Publishing 2017) 100.

[119]William MacAskill, *What We Owe The Future* (1st Trade Paperback edn, Basic Books 2023).

[120]On the distinction between 'empirical' (epistemic) and 'normative' uncertainty, see: Franz Dietrich and Brian Jabarian, 'Decision under Normative Uncertainty' (2022) 38(3) *Economics and Philosophy* 372.

[121]Somsen (n 112) 357, 365.

[122]eg, Louis J Kotzé (ed), *Environmental Law and Governance for the Anthropocene* (Hart Publishing 2017); Louis J Kotzé and Rakhyun E Kim, 'Earth System Law: The Juridical Dimensions of Earth System Governance' (2019) 1 *Earth System Governance* 100003; Garver (n 44).

[123]Bowman, Rip and Stokes (n 5) 3.

[124]Bennett Moses (n 6) 766; Jorge E Viñuales, 'The Organisation of the Anthropocene' (2018) 1(1) *BRP International Legal Theory and Practice* 1.

[125]Ialenti (n 9); Stokes (n 4); Leach (n 4), 7.

[126]Toulmin (n 42).

[127]Jonas (n 2) 17; Jonas (n 43) 21–22.

[128]Kevin D Burke and others, 'Pliocene and Eocene Provide Best Analogs for Near-future Climates' (2018) 115(52) *Proceedings of the National Academy of Sciences of the United States of America* 13288.

carbon dioxide concentrations are now 50% higher than at any time in human civilizational history; substantially higher than when humans developed written laws[129] and agriculture, or when humans were hunter-gatherers.[130] 'Wisdom' is without experiential domain in the Anthropocene. In contrast, other scholars demystify the grand Anthropocene concept, deconstructing it to its underlying drivers to try to 'work with' processes of change.[131] Some boldly suggest how law might adapt to these ecotechnological times[132] or how present societies should philosophise about the far future.[133]

Yet in essence, each of these transformative future visions amounts to a reversion to the past.[134] Law is no stranger to such normative uncertainty and retrospection,[135] with law's conceptual machinery 'reengineered' time and time again.[136] This perpetuates a long human cultural tradition of reinventing concepts from the past to serve new purposes, particularly in response to new technologies.[137] Confronted with the profound sociotechnical-environmental entanglements of the Anthropocene, this article argues that old and existing concepts should once again be reinvented to reflect the changed sociotechnical environment and address contemporary governance challenges.[138]

As a starting point, anticipatory governance in the Anthropocene could look to alternative bases for certainty. The antonym of *un*certain is certain, which derives from the Latin *certus*, as the past participle of *cernĕre* (to decide, determine).[139] This highlights an important distinction between deciding and determining something and points to differing bases for certainty. The verb determine is directed at ends and limits, from the Latin *dētermināre* (to bound, limit, fix; to set bounds to).[140] This teleological

[129]S N Kramer, 'Ur-Nammu Law Code' (1954) 23(1) *Orientalia* 40; J J Finkelstein, 'The Laws of Ur-Nammu' (1968) 22(3–4) *Journal of Cuneiform Studies* 66.

[130]Jan Zalasiewicz, '4. The Extraordinary Strata of the Anthropocene' in Akeel Bilgrami (ed), *Nature and value* (Columbia University Press 2020) 38; Stainforth (n 37) 54, 252.

[131]For example, Malm and Hornborg (n 19); J E Viñuales, 'A Concise Research Agenda for Environmental Law' [2018] *Brill Open Law* 1; López-Corona and Magallanes-Guijón (n 19); Leach (n 4).

[132]For example, Teubner (n 66); Leach (n 4).

[133]For example, MacAskill (n 119).

[134]Most obviously in Toulmin's clarion call for a 'return to reason': Toulmin (n 42); but also in 're-engineering' existing legal conceptual machinery for new social actors: Teubner (n 66); a return to Marx: Malm and Hornborg (n 19) 67, and Teubner (n 66) 521; or, by extending the analogy of 'expected utility theory' from empirical to normative uncertainty: William MacAskill, 'Normative Uncertainty' (PhD thesis, University of Oxford 2014); MacAskill (n 119).

[135]Dryzek (n 32); Kotzé and Kim (n 122); Garver (n 44); Joshua C Gellers, 'Earth System Law and the Legal Status of Non-humans in the Anthropocene' (2021) 7 *Earth System Governance* 100083; Leach (n 4).

[136]Teubner (n 66) 515; Gellers (n 135).

[137]Ialenti (n 9) 36.

[138]Viñuales (n 131) 9.

[139]'certain, adj, n & adv' (*OED Online*, OUP December 2023) <www.oed.com/dictionary/certain_adj?tab=factsheet#9732757> accessed 5 June 2024.

[140]'determine, v' (*OED Online*, OUP December 2023). <www.oed.com/dictionary/determine_v?tab=factsheet#7056462> accessed 5 June 2024.

focus stands in contrast to the original, now obsolete meaning of the verb to decide, from the Latin *dēcīdere* (to cut off, cut down).[141] To decide something is to arrive at an opinion or conclusion, about which there may be still some doubt, after considering alternatives.[142] Thus, while certainty may be either determined or decided, to determine is clearly more definitive than to decide. However, determinism is a discredited ideal of modernity; chaos reigns in the Anthropocene.[143] In the climate change example, we cannot *determine* the future climate ex ante; we can only *decide* between alternative possible futures.

Law does not provide a timeless recipe for 'correct' decisions,[144] but it does offer rules and governance procedures for arriving at 'good' decisions.[145] Thus, law and DMDU share a common aim. While circumstances differ by regulatory context, in general lawyers typically follow a 'rule-facts-judge' pattern in reaching a legal decision.[146] This 'ancient'[147] legal formula appears to represent a compromise between two extremes: the impossibility of some universally valid decision rule[148] and the intolerable arbitrariness of individual discretion.[149] Rather, the formula aims to make transparent the 'tragic' choices inherent in any decision,[150] which involve trade-offs between competing values and interests.[151] Without prescribing the outcome, but by prescribing structure and what information to consider and how, such legal formulas regulate important public policy decisions. To these ends, the emerging technologies and practices of DMDU could be integrated with law, largely within the scope of existing anticipatory governance frameworks.[152]

Having taken these bearings of the existing sociotechnical landscape, we turn now to consider DMDU analysis in more detail.

3. Decision making under deep uncertainty (DMDU)

The DMDU community offers several methods for decision support under deep uncertainty. These are broadly described as exploratory modelling

[141] 'decide, v' (*OED Online*, OUP December 2023). <www.oed.com/dictionary/decide_v1?tab=factsheet#7324134> accessed 5 June 2024.
[142] Ibid.
[143] Toulmin (n 42) ch 4.
[144] Lief H Carter and Thomas F Burke, *Reason in Law* (9th edn, The University of Chicago Press 2016) ch 1.
[145] Jasanoff (n 52) 7–11; Carter and Burke (n 144) 25–26.
[146] Ialenti (n 9); See also Carter and Burke (n 144) ch 1 (for a similar formula).
[147] Ialenti (n 9) 38–40.
[148] Toulmin (n 42) 27; Hart (n 73), 662.
[149] Carter and Burke (n 144) 20–21.
[150] Ibid 25–26.
[151] Wojciech Sadurski, 'Reasonableness and Value Pluralism in Law and Politics' in Giorgio Bongiovanni, Giovanni Sartor and Chiara Valentini (eds), *Reasonableness and Law* (vol 86, Springer Netherlands 2009) 140–141.
[152] Bennett Moses (n 6) 766.

techniques, which emerged from operations research.[153] DMDU methods include Robust Decision Making (RDM), Dynamic Adaptive Planning, Dynamic Adaptive Policy Pathways (DAPP), Info-Gap Theory (IG), and Engineering Options Analysis.[154] The focus here is on RDM, a 'paradigm example' of DMDU,[155] but different methods will suit different decision-making contexts.[156] All DMDU approaches use the same basic steps shown in Figure 3. Each DMDU step is discussed briefly below, drawing general parallels with legal decision-making. In the following section, law and DMDU are discussed more deeply using four theoretical 'lodestars'.

At the outset, we must define four keywords in DMDU terminology. Firstly, a 'future' or 'future state of the world' refers to a specific set of assumptions about conditions that lay ahead (e.g. future climate data). A DMDU analysis typically uses multiple futures to represent uncertainty.[157] Second, a 'policy' means a decision-maker's distinct choice among a suite of alternatives (e.g. between different climate policy instruments, or between different carbon prices in one instrument). In DMDU analyses, policies may vary in magnitude, location or timing.[158] Third, a 'case' means a single model run for one future and one policy (e.g. one set of future climate conditions and one climate policy). A DMDU analysis will generate a vast database of many model runs and hence many cases.[159] Finally, in RDM and other methods using 'scenario discovery', a 'scenario' is a cluster of cases with common decision-relevant outcomes of interest (e.g. a cluster of cases in which a given policy succeeds/fails).[160] We use these terms repeatedly below.

Now refer back to Figure 3. At this level of abstraction, we can identify the basic building blocks of a complementary legal framework, following typical legal design patterns:[161]

(1) In **decision framing**, law could prescribe what information must be considered, ie *what* futures and policies, and *who* should participate.[162] We

[153]Lempert (n 36) 26–30; Marchau and others (eds) (n 35) 393–394.
[154]Marchau and others (eds) (n 35).
[155]Jan H Kwakkel, Sibel Eker and Erik Pruyt, 'How Robust is a Robust Policy? Comparing Alternative Robustness Metrics for Robust Decision-making' in Michael Doumpos, Constantin Zopounidis and Evangelos Grigoroudis (eds), *Robustness Analysis in Decision Aiding, Optimization, and Analytics* (International Series in Operations Research & Management Science, Springer International Publishing 2016) 222.
[156]For example, combinations of methods, like RDM & DAPP or RDM & IG, may be complementary: Jan H Kwakkel, Marjolijn Haasnoot and Warren E Walker, 'Comparing Robust Decision-making and Dynamic Adaptive Policy Pathways for Model-based Decision Support under Deep Uncertainty' (2016) 86 *Environmental Modelling & Software* 168.
[157]Marchau and others (eds) (n 35) 403.
[158]Policies may also be adaptive, consisting of 'initial' and 'contingent' actions (ie, if *x* climate or policy event happens, then *y* alternative policy is introduced …): ibid 403.
[159]Ibid 402.
[160]In other contexts, 'scenario' may sometimes be synonymous with 'future' or 'case': ibid 404.
[161]Wernick (n 23).
[162]Of course, other law(s) would also delineate further boundary conditions or the overall scope of any decision, such as who is affected, in what way, what the legal consequences of decision would be, etc., but such broader considerations are beyond the scope of this article.

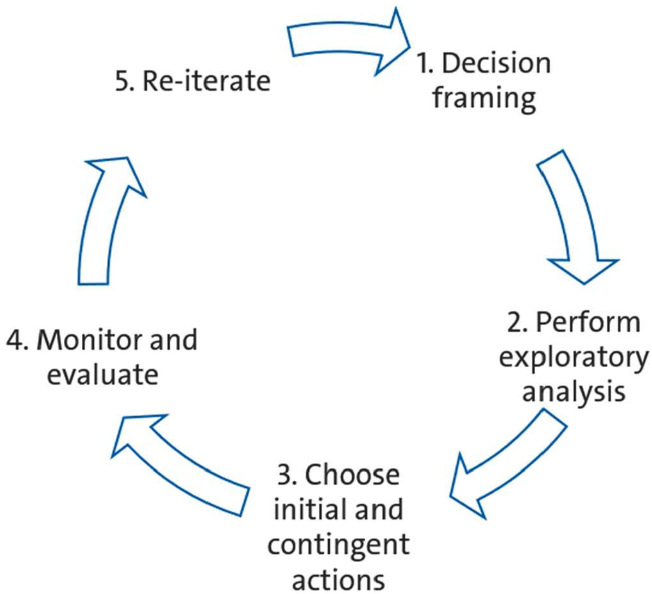

Figure 3. Overview of the steps involved in most DMDU methods. (Visualisation by author, based on Marchau et al. 2019, pp 12–15).

discuss this further under the concepts of rationality, relevance and reasonableness below.

(2) In the **exploratory analysis** step, law could regulate how to perform DMDU analysis, i.e. *which* futures, policies, cases and scenarios and *to what extent*. This might include minimum standards of exploration across future, policy or case parameters, like 'business-as-usual' and 'best/worst' scenarios. In time, law could also impose professional standards or standard operating procedures on DMDU analysts. We discuss this further under the concepts of relevance and reasonableness below.

(3) In **choosing between available actions**, law could prescribe *who* should participate; *what* procedures must be followed; and *how* policymakers should decide between options.[163] We discuss this further under the concepts of relevance, reasonableness and robustness below.

(4) **Monitoring and evaluation** is classic environmental law and could be integrated with the fifth step, **reiteration** of the analysis. Law could require monitoring, evaluation and reiteration at regular intervals or contingent on some prescribed event. Given clear parallels in existing environmental law, we do not discuss these steps in this article.

[163]Note some DMDU analyses identify 'initial' actions to be decided now and 'contingent' actions to be decided in future. Depending on implementation, contingent actions could raise concerns about self-executing law, fettering future discretion or even legislative entrenchment, but these issues are beyond the scope of this article.

We note that these generic DMDU steps are broadly consistent with rules of thumb for deep uncertainty in moral philosophy.[164] However, more specific ethical-legal analysis of enabling frameworks for DMDU requires careful consideration of case studies. That is beyond this article's scope. Instead, with these vague outlines of a law-and-DMDU navigation device, we now explore how it might be interpreted from a theoretical perspective.

4. Lodestars of principle: the four Rs

In this section, we set sail with our rudimentary law-and-DMDU navigation device, pointing it at four theoretical *lodestars of principle*, the 'Four Rs': rationality, relevance, robustness and reasonableness.

4.1. Rationality

Any governance process aims to be rational in that it follows some logic.[165] Logic in a legal sense includes both the science of reasoning and the operations of understanding subservient to estimation of evidence.[166] Thus, rationality (the science of reasoning) and relevance (a subservient operation) are closely related concepts.

Legal rationality[167] is a chameleon concept, transforming to suit changing circumstances in different legal contexts.[168] Some claim that legal reasoning is logically deductive,[169] while others think it is based on multivalent degrees of belief.[170] Yet some things cannot be reduced to rules,[171] and the life of the law has famously not been logic; it has been experience.[172] In practice, law accommodates many ways of reasoning, including formal logic but also 'metaphors, analogical reasoning, infinite regresses, transcendental argumentation … whatever … may be appropriate in the context of some

[164]Namely, (1) take actions that we can be comparatively confident are good, (2) try to increase the number of options open to us, and (3) try to learn more: MacAskill (n 119) 226.

[165]From the Greek 'logos', meaning 'the whole spectrum of reasoning and thought': Toulmin (n 42) 25–26.

[166]'logic', *Black's Law Dictionary* (6th edn, West Publishing Co 1990) 942.

[167]Various Latin maxims about 'ratio' indicate law's polyrationality discussed here: *Black's Law Dictionary* (Henry Campbell Black and others (eds) (6th edn, West Publishing Co 1990)) 1262–1263; cf 'irrational' 829.

[168]R J Allen, 'Taming Complexity: Rationality, The Law of Evidence and the Nature of the Legal System' (2013) 12(2) *Law, Probability and Risk* 99. See also: Viñuales (n 124) 14–15.

[169]For example, the claim that deduction could resolve '90 percent of legal issues': Ruggero J Aldisert, Stephen Clowney and Jeremy D Peterson, 'Logic for Law Students: How to Think Like a Lawyer' (2007) 69(1) *University of Pittsburgh Law Review* 2.

[170]For example, a trier-of-fact's sequential reasoning through the elements of a crime or cause of action, to which they assign a degree of belief either consciously or unconsciously: Kevin M Clermont, 'The Logic of Uncertainty in Law and Life' (2020) 19(2) *Law, Probability and Risk* 181.

[171]Allen (n 168) 109, footnote 36; See also: Toulmin (n 42) 27; See also generally Lorraine Daston, *Rules: A Short History of What We Live By* (Princeton University Press 2022).

[172]Oliver W Holmes, *The Common Law* (The John Harvard library, The Belknap Press of Harvard University Press 2009) 3; Alschuler (n 78).

case'.[173] This 'organic and not static' way of reasoning makes legal logic exceedingly difficult to codify in artificial intelligence.[174] The point here is that legal rationality is plural, with various logical structures available 'off the shelf'. In practice, 'rationality' depends on broader societal values and institutional settings, so the challenge is to match reasoning to relevant context.[175] Here we are most interested in the logic of a regulator or legislator, while appreciating the interpretive challenges ahead for the judiciary. To this end, there is a discernible logical pattern in the design of most existing sociotechnical anticipatory governance regimes for impact assessment.[176] This logical pattern appears to have influenced the design and development of DMDU's own practices, considered below, and it is in such areas of law that DMDU finds its most obvious applications.

An essential first step in any reasoning process is to marshal and process information. DMDU methods gather and organise data systematically using the 'XLRM' matrix.[177] XLRM stands for the following information considered relevant to any decision under deep uncertainty:

- known or identified e**x**ogeneous uncertainties;
- available policy **l**evers under decision-maker control;
- known or suspected **r**elationships between policy levers and measures of success; and
- known **m**easures of success or key performance criteria.[178]

The XLRM matrix is a fundamental building block in any DMDU analysis. The matrix data is fed into some analytic model,[179] which is used in an exploratory way.[180] A DMDU analyst may use or adapt an existing model, or construct a model afresh.[181] RDM analyses typically use complex models,[182] but 'fast and simple' models[183] and even RDM without formal models[184] may be useful. The aim here is to generate a wide variety of 'guesses'

[173]Allen (n 168) 107.
[174]Ibid 107.
[175]Ibid 101.
[176]Riikka Koulu and Jörg Pohle, 'Legal Design Patterns: New Tools for Analysis and Translations Between Law and Technology' (2024) 3(2) *DISO*; Wernick (n 23).
[177]Also known as the 'XPROW' framework: Marchau and others (eds) (n 35), 4–5, 261–262.
[178]Note that these measures or criteria may be prescribed by law.
[179]See definitions of 'Analytic model', 'Exploratory Modeling' and 'Fast Simple Model': Marchau and others (eds) (n 35) 401–402.
[180]In contrast to a 'consolidative' (validated, predictive) model, an 'exploratory' model inductively 'maps' assumptions to consequences, without validating alternative assumptions: ibid.
[181]Popper (n 41) 385.
[182]Ibid 386–387; multi-objective RDM (MORDM) is capable of machine-generated policies: Lempert (n 36) 33.
[183]Popper (n 41) 387; Thompson (n 96) chs 2, 8; Stainforth (n 37) chs 6, 15–16.
[184]Steven W Popper, 'Robust Decision Making and Scenario Discovery in the Absence of Formal Models' (2019) 1(3–4) *Futures & Foresight Science*.

about how the future may unfold.[185] Each guess represents an individual run of the model for one future (the input parameters in X) and one policy (the input parameters in L). Each guess is known as a 'case'.[186] Having generated very many cases,[187] the next step is to sample clusters of interesting cases.

There are three main case sampling strategies: 'exploration', 'search' or 'pre-defined' strategies.[188] 'Exploration' strategies systematically and inductively sample across all cases. Techniques include Monte Carlo sampling, Latin Hypercube sampling, or statistical factorial methods.[189] A key difference between Monte Carlo and Latin Hypercube sampling is that the former samples randomly, while the latter samples 'all corners' of cases. In other words, Monte Carlo sampling is like aiming randomly at a dartboard, whereas Latin Hypercube sampling lands a dart in each ring and radial section of the dartboard. Latin Hypercube is more comprehensive, more reproducible and less computationally intensive than Monte Carlo sampling. RDM traditionally uses Latin Hypercube. By contrast, 'search' strategies are more forensic and pre-informed. 'Search' strategies use multi-objective optimisation techniques to sample best or worst cases, or to compare case performance across particular futures or policies. Finally, 'pre-defined' strategies are more deductive, avoiding systematic exploration and instead homing in on particular futures or policies and how the uncertainties affect them.[190]

In summary, both law and DMDU exhibit plural rationalities. While XLRM is quite strictly rational, this is not as foreign to the law as it may seem. In the context of evaluating a particular regulatory decision by a court, lawyers often talk about the 'matrix' surrounding a decision.[191] XLRM explicitly populates this matrix with available information, which could improve governance transparency. Further, DMDU sampling strategies reflect the variety in legal rationality, with adaptability in different decision contexts. For any given XLRM matrix and sampling strategy, the question then becomes: how can decision-making remain manageable when considering such enormous numbers of cases? This is where relevance comes to the fore.

4.2. Relevance

Relevance is a concept that transcends fields of law. While a regulator may be expected prospectively to take into account all 'relevant' considerations,

[185]Lempert, Popper and Bankes (n 18) 43–46.
[186]Marchau and others (eds) (n 35) 402.
[187]Typically, thousands or millions of cases.
[188]Jan H Kwakkel and Marjolijn Haasnoot, 'Supporting DMDU: A Taxonomy of Approaches and Tools' in Vincent A W J Marchau and others (eds), *Decision Making under Deep Uncertainty* (Springer International Publishing 2019) 363–364.
[189]Ibid 363.
[190]Ibid 363–364.
[191]For example, Hart (n 73) 659, 663–664.

relevance often plays a role in retrospectively evaluating decisions or conduct in the context of rules of evidence.[192] The term 'relevant evidence' was recently interpreted by the European Court of Justice to mean three things: 'relevant, proportionate and necessary'.[193] The first limb is clearly circular, but the necessity limb requires some logical connection between the evidence and a fact in issue. This reinforces the concept of 'rationality' above. Meanwhile, the proportionality limb echoes constitutional rights jurisprudence, where proportionality mediates between 'necessity' and 'reasonableness'.[194] In most constitutional rights cases, proportionality often amounts to whether or not state action is *relevant* to achieving some public policy aim.[195] Thus, this is one example of how relevance mediates between the concepts of rationality and reasonableness.

It was noted earlier that relevance is a subservient operation in higher-level reasoning.[196] Legal relevance focuses attention on the quality and capability of information to prove logically necessary facts.[197] Relevance informs the factfinder's perception of probability and thus the strength of the inferences drawn from the evidentiary information.[198] Tests of relevance therefore refer to standards of applicability and pertinence, whether absolute or probable, self-evident or tendential, and may look to the past, present, or future.[199] That is, relevance tests establish and reinforce the constitutive logical relationships between evidence and fact that are ultimately necessary to form conclusions of law.[200] In these ways, relevance plays a key role in the familiar 'rule-facts-judge' formula of legal reasoning.[201]

Two relevance tests grounded in this basic theory could complement DMDU. The tests would focus on the quality and capability of certain model output 'case' information to pique our interest in particular manifestations of the future. This information need not be absolute and could be merely probable or tendential.[202] The tests could also apply to prospective

[192] Jasanoff (n 52) 10, 230–231; US Fed R Evid (1 December 2023) Art IV.

[193] *Case C-163/21 AD v PACCAR Inc, DAF Trucks NV, DAF Trucks Deutschland GmbH* (2022), para 69; Council Directive 2014/104/EU of 26 November 2014 on certain rules governing actions for damages under national law for infringements of the competition law provisions of the Member States and of the European Union [2014] OJ 2014 L349/1, Art 5.

[194] For example, Sadurski (n 151) 134–135.

[195] Ibid 135, 140.

[196] See 'logic' (n 166).

[197] US Fed R Evid (n 192) 401; see 'relevancy' and 'relevant evidence'; cf 'irrelevancy', *Black's Law Dictionary* (6th edn, West Publishing Co 1990) 829, 1290–1291.

[198] Clermont (n 170) 190–195; cf 'relevant evidence', 'probability', 'probable' and 'probably', *Black's Law Dictionary* (6th edn, West Publishing Co 1990) 1201, 1291.

[199] 'relevancy', *Black's Law Dictionary* (6th edn, West Publishing Co 1990) 1290–1291.

[200] Cf 'relevancy', 'relevant evidence' and 'logical relevancy', *Black's Law Dictionary* (6th edn, West Publishing Co 1990) 942, 1290–1291.

[201] Ialenti (n 9).

[202] 'relevancy', *Black's Law Dictionary* (6th edn, West Publishing Co 1990) 1290–1291.

future ‘facts’, including alternative matrices of futures and policies.[203] In other words, legal relevance tests could apply to different computations of future climate conditions and future climate policies. This will be considered in more detail below, but to avoid becoming lost in the technical complexity of DMDU, let us first recall the XLRM matrix. The first relevance test could operate prospectively and assist in populating this matrix with all *relevant* information.

The second relevance test would operate later, but to understand how, we must first consider the basic function of computer modelling. Once the XLRM matrix is populated, the basic task in any DMDU analysis is to run a model (R), across a range of exogeneous uncertainties (X) and alternative policy levers (L). The X and L represent two model inputs, connected via some relationship, R. A computer model operates on a strictly rational basis, generating all possible combinations of X and L, for some relationship R. Once the model has computed outputs, these will be interpreted against the measures for success (M). The ultimate interpretative task is to assess the *reasonableness* of these model outputs. This basically means that model interpretation is a test of the plausibility of all possible *rational* combinations of X and L. Thus, keeping in mind the traditional role of *relevance* in mediating between the *rational* and *reasonable*, a second relevance test could help mediate between all possible model outputs and a narrower range of more plausible model outputs.[204] We now return to technical DMDU theory to understand how this might work.

In the modelling process just described, a DMDU analysis generates thousands or millions of ‘cases’. These cases are then sampled using the different search strategies discussed earlier.[205] One of DMDU’s methodological innovations, pioneered in RDM,[206] was to sample among these cases to generate ‘scenarios’ inductively, *during* the analysis. In contrast, traditional scenario analysis generates descriptive scenarios in discussion with stakeholders, *before* any analysis. RDM’s inductive scenario generation process is called ‘scenario discovery’.[207] This can be achieved with various qualitative or

[203]By analogy to what already occurs when courts decide between competing ‘constellations’ of constitutional values. Regardless who ‘wins’, alternative matrices of constitutional values remain valid and there is an ‘implicit promise’ that the losing party could prevail under a different future factual matrix: Sadurski (n 151) 140–141.

[204]By analogy to a common role for reasonableness, which mediates between ‘the abstract and the concrete’: Giorgio Bongiovanni, Giovanni Sartor and Chiara Valentini (eds), *Reasonableness and Law* (86, Springer Netherlands 2009) xiii.

[205]Refer *4.1 Rationality*.

[206]Lempert, Popper and Bankes (n 18); Robert J Lempert and others, ‘A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios’ (2006) 52(4) *Management Science* 514.

[207]Lempert, Popper and Bankes (n 18); Benjamin P Bryant and Robert J Lempert, ‘Thinking Inside the Box: A Participatory, Computer-assisted Approach to Scenario Discovery’ (2010) 77(1) *Technological Forecasting and Social Change* 34. See also definition of ‘Scenario Discovery (SD)’: Marchau and others (eds) (n 35) 404.

quantitative tools.[208] A common tool in RDM is the Patient Rule Induction Method (PRIM) algorithm.[209] The name comes from the 'patient' way the algorithm iteratively and inductively selects between millions of cases.[210] More advanced, multi-objective RDM uses evolutionary algorithms for scenario discovery.[211] Finally, an important transparency feature in DMDU analyses is that, even after the process of scenario discovery, any particular case (among the very many) can still be accessed manually.[212]

Two DMDU concepts are integral to scenario discovery and serve to constrain the analysis: density and coverage.[213] *Density* describes the number of decision-relevant cases within any area sampled by the algorithm. *Coverage* refers to the proportion of all decision-relevant cases included in the area sampled. The difference between density and coverage is illustrated in Figure 4, for hypothetical parameters, x_{1-4}. Ideally, all decision-relevant cases would be sampled with both 100% density and coverage.[214] However, this would not reflect realistic decision-making, so scenario discovery has a third competing constraint: interpretability.[215] This represents a compromise necessary to reduce the complexity of millions of cases to a workable number of scenarios for human cognition. Here the idea of 'decision-relevance' is key. Recall that the 'M' in XLRM identifies measures for success, typically representing some critical 'pass/fail' threshold.[216] DMDU uses these performance metrics to inform interpretability.[217] As a rule of thumb, in balancing the three constraints, DMDU analysts aim for about 75% density, where any sampling 'box' includes about 75:25 pass:fail outcomes.[218]

In less technical terms, scenario discovery represents a model-based policy 'stress test'. It 'discovers' different combinations of X-L-R by reference to whether or not they achieve some critical level of performance, M.[219] By trading off between the constraints of density, coverage and interpretability, scenario discovery tools sample particularly interesting clusters of cases,

[208]Patrick M Reed and others, *Addressing Uncertainty in Multisector Dynamics Research* (Zenodo 2024) 30–33.
[209]Jerome H Friedman and Nicholas I Fisher, 'Bump Hunting in High-dimensional Data' (1999) 9(2) *Statistics and Computing* 123; David G Groves and Robert J Lempert, 'A New Analytic Method for Finding Policy-relevant Scenarios' (2007) 17(1) *Global Environmental Change* 73; Bryant and Lempert (n 207).
[210]Friedman and Fisher (n 209) 128–129.
[211]Such as classification and regression trees (CART), gradient-boosted trees, random forest, and logistic regression: Lempert (n 36); Reed and others (n 208) ch 4.
[212]Popper (n 41) 388.
[213]Groves and Lempert (n 209); Bryant and Lempert (n 207).
[214]Bryant and Lempert (n 207).
[215]Groves and Lempert (n 209); Bryant and Lempert (n 207).
[216]For example, we could well imagine that a law would mandate some minimum level of performance, such as in the utilities sector, or minimum level of adaptation to climate risks, such as flooding or sea-level rise.
[217]Bryant and Lempert (n 207).
[218]Ibid.
[219]Lempert (n 36) 31; Kwakkel and Haasnoot (n 188).

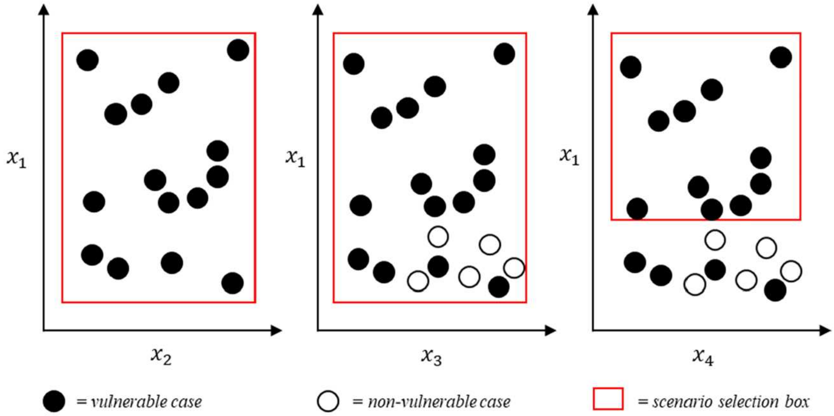

Figure 4. Visualising density and coverage in the scenario discovery process. The left sample box has density = 1 and coverage = 1; the middle box has density = 0.75 and coverage = 1; the right box has density = <1 and coverage = <1. (Visualisation by author, based on Bryant and Lempert (2010)).

from among the millions of possible cases. In the inductive process described above, each cluster sample 'discovered' is known as a scenario. Each scenario will include cases spanning a very wide range of model inputs (X, L and R), but the common characteristic of all cases in one scenario is that they all achieve similar performance (M). Thus, scenario discovery tools perform a kind of 'principal component analysis' of inputs that drive success (or failure) in any scenario.[220] As an important safeguard and in the interests of transparency, any case could still be accessed manually at any time. But, by reducing multidimensional case information to a manageable number of scenarios, scenario discovery tools produce probative, practical information. That is, because all cases in any one scenario share something in common, scenario discovery tools provide information of potential value to policymakers. Thus, the second relevance test discussed earlier would be directed at this probative information and integrate the concept of relevance with a 'scenario discovery' tool.

In summary, two relevance tests could complement DMDU. The first test could populate the XLRM matrix with all relevant information. We will return to this test below.[221] The second test could be based on some relevant pass/fail performance criterion and be integrated with a scenario discovery tool. To understand how all this might work in practical governance, we must now turn to the typical outputs of a DMDU analysis and the concept of robustness.

[220] S Dalal and others, 'Improving Scenario Discovery Using Orthogonal Rotations' (2013) 48 *Environmental Modelling & Software* 49; Lempert (n 36).
[221] See *4.4 Reasonableness*, below.

4.3. Robustness

In taking our bearings earlier, we distinguished between deciding and determining something. Here we are interested in how to decide between options. Ultimately, regulators must m take a decision and set a policy or pass a law, whereupon they are held accountable to external legal standards.[222] Under deep uncertainty, quantified standards would be arbitrary and contrary to the idea of open, agentic futures.[223] Moreover, legal traditions that eschew quantification[224] and prefer to learn by experience[225] are likely to be hostile to such standards. Yet even 'reasonable' standards must be imbued with some substance.[226] This is where the DMDU concept of robustness comes to the fore.

Robustness is an engineering concept, defined as 'insensitivity of system design to errors, random or otherwise, in the estimates of those parameters affecting design choice'.[227] Robustness is distinguished from the similar concept of resilience by a shift in perspective; robustness considers how different design choices affect a system *from within*, whereas resilience refers to a system's broader properties[228] viewed *from without*.[229]

In DMDU jargon, all robustness metrics aim, in the presence of uncertainty about inputs, to find 'optimal' outputs insensitive to any specific realisation of the uncertain inputs.[230] This is categorically different to attempts to identify a single best, 'optimal' policy choice. Some regulatory impact assessments already require uncertainty analysis towards a 'robust' result,[231] but this is different to the DMDU robustness concept. Rather, DMDU methods aim to achieve robust decisions by asking: what would it take for a given policy to fail to achieve its goals?[232] A robust policy is one with good performance across a wide range of futures.[233] This raises the question: what constitutes 'good' performance? The diversity in DMDU robustness metrics reflects the diversity of possible answers to this question.

[222]Even if standards vary, such as 'reasonable care': Hart (n 73) 663.
[223]Stirling (n 40).
[224]Larry Laudan, 'Is Reasonable Doubt Reasonable?' (2003) 9(4) *Legal Theory* 295 312.
[225]Alschuler (n 78); Hart (n 73).
[226]Laudan (n 224); Robert Alexy, 'The Reasonableness of Law' in Giorgio Bongiovanni, Giovanni Sartor and Chiara Valentini (eds), *Reasonableness and Law* (vol 86, Springer Netherlands 2009), 13–15.
[227]Nicholas C Matalas and Myron B Fiering, 'Water-Resource Systems Planning' in National Research Council (ed), *Climate, Climatic Change, and Water Supply* (National Academies Press 1977) 106; Ariella Helfgott, 'Operationalizing Resilience: Conceptual, Mathematical and Participatory Frameworks for Understanding, Measuring and Managing Resilience' (PhD thesis, University of Adelaide 2015) 93.
[228]For example, resilience overlaps robustness, but also extends to system stability and adaptability: Helfgott (n 227) 94.
[229]Lempert, Popper and Bankes (n 18) 54, footnote 14; J M Callaway and others, 'The Economics of Adaptation: Concepts, Methods and Examples' (Copenhagen 2016) 133.
[230]Kwakkel, Eker and Pruyt (n 155) 223.
[231]See, for example, 'EU Better Regulation Toolbox – July 2023': European Commission (n 28) 567.
[232]Marchau and others (eds) (n 35) 395, 403–404 ('Objectives' and 'Robust policy').
[233]Lempert, Popper and Bankes (n 18) 53–57; Lempert (n 36) 34–35; Kwakkel and Haasnoot (n 188) 364.

A basic distinction exists between 'regret' and 'satisficing' metrics.[234] Regret measures the difference between a specific policy and some baseline policy in a specific future.[235] This distinguishes the DMDU notion of regret from the axiomatic 'maxmin' rule, which simply chooses the policy with the least worst possible outcome.[236] Rather, the RDM idea of regret is similar to Savage's 'minmax regret' rule, which minimises the difference between the best possible option in any future and the actual choice.[237] However, RDM expands the minmax rule by looking at multiple options and relative improvements, in iterative deliberation.[238] Other regret approaches take a baseline policy in a particular state of the world rather than the best.[239] In contrast, satisficing metrics operationalise the practice of policymakers who reach satisfactory or sufficient, but not 'optimal' decisions.[240] Satisficing metrics maximise the number of future states of the world in which a policy achieves some minimum standard,[241] such as a technical safety threshold or achievement of the 2-degree climate target.[242] A common metric is the utilitarian 'domain criterion', centred on critical performance thresholds.[243] Still other (non-regret, non-satisficing) metrics seek to capitalise on the potential upsides of uncertainty.[244] Further nuances between metrics are discussed extensively by DMDU,[245] economics,[246] and law-and-economics scholars.[247] In summary, the choice of robustness metric is highly context-dependent. For these reasons, DMDU analysts often test multiple robustness metrics, iteratively, in close collaboration with stakeholders.[248]

[234]Kwakkel, Eker and Pruyt (n 155) 223; Kwakkel and Haasnoot (n 188) 364–365.
[235]Ibid.
[236]Sunstein (n 31) ch 3; Geoffrey Heal and Antony Millner, 'Reflections- Uncertainty and Decision Making in Climate Change Economics' (2014) 8(1) *Review of Environmental Economics and Policy* 120 131–132.
[237]Leonard J Savage, *The Foundations of Statistics* (2nd rev edn, Dover Publications 1972) chs 9, 13; Heal and Millner (n 236) 131–132.
[238]Lempert, Popper and Bankes (n 18) 53, footnote 13, discussing the inherent worth of wide variety in values and options, rather than best and worst, as justification for modifying Savage's approach; Lempert and others (n 206) 516–518; Robert J Lempert and Myles T Collins, 'Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches' (2007) 27(4) *Risk Analysis* 1009, 1018.
[239]Kwakkel and Haasnoot (n 188) 364–365.
[240]Lempert, Popper and Bankes (n 18) 54; Kwakkel and Haasnoot (n 188) 364.
[241]Kwakkel and Haasnoot (n 188) 364.
[242]Gregor Betz, 'Accounting for Possibilities in Decision Making' in Sven O Hansson and Gertrude Hirsch Hadorn (eds), *The Argumentative Turn in Policy Analysis: Reasoning about Uncertainty* (Springer 2016) 149.
[243]Lempert (n 36) 34–35; Kwakkel and Haasnoot (n 188) 364.
[244]Lempert, Popper and Bankes (n 18) 54; Kwakkel and Haasnoot (n 188) 364–365.
[245]Kwakkel, Eker and Pruyt (n 155); C McPhail and others, 'Robustness Metrics: How Are They Calculated, When Should They Be Used and Why Do They Give Different Results?' (2018) 6(2) *Earth's Future* 169; Lempert (n 36) 34–35.
[246]For a review, see Heal and Millner (n 236).
[247]E.g. Sunstein (n 31) ch 3; Weisbach (n 31).
[248]Kwakkel, Eker and Pruyt (n 155); McPhail and others (n 245); Kwakkel and Haasnoot (n 188).

Law could complement DMDU's search for robust policies and decisions. First, law could define robustness by drawing on 'law-and-resilience' work,[249] given the conceptual overlap between resilience and robustness.[250] However, law should eschew any universal robustness metric. While a satisficing metric and minimum standards may be more appropriate in critical infrastructure laws,[251] other areas of law seem better suited to regret metrics.[252] In either case, robustness could be a useful concept in giving substance to the second relevance test identified earlier. Where clear minimum standards are prescribed by law, this may be straightforward.[253] But where policy goals are more nebulous, political or subject to value contestation, different robustness metrics will mean different things to different people;[254] a 'robust' decision is something about which reasonable minds may differ. However, policy pass/fail thresholds–the bottom line for decision-makers–remain a common and therefore generally applicable locus for a relevance test. Just as 'relevant evidence' is open to interpretation, a 'relevant threshold' would permit different choices of robustness metric and so different interpretations of robust decisions. This now leads us to the issue of flexible external standards for assessing robustness and so we turn to reasonableness.

4.4. Reasonableness

Reasonableness is a 'workhorse'[255] of legal theory across common and civil law traditions.[256] Ideas such as fairness, justice, reason and 'good judgement' are essential to reasonableness.[257] These are the qualities of reasonableness that set it apart from the narrower concept of rationality;[258] reason takes a broader range of indefinite factors into account, about which 'reasonable

[249]E.g. Verschuuren (n 112) 21; Catherine Banet and others (eds), *Resilience in Energy, Infrastructure, and Natural Resources Law: Examining Legal Pathways for Sustainability in Times of Disruption* (1st edn, Oxford University Press 2022).

[250]Helfgott (n 227) 93–94.

[251]For example, electricity or water supply.

[252]For example, proportionality tests of constitutional rights are analogous to minimising regret: Sadurski (n 151) 140–141; Giovanni Sartor, 'A Sufficientist Approach to Reasonableness in Legal Decision-making and Judicial Review' in Giorgio Bongiovanni, Giovanni Sartor and Chiara Valentini (eds), *Reasonableness and Law* (vol 86, Springer Netherlands 2009); Lino Munaretto, 'Fundamental Rights and Limited Possibilities: The Proviso of the Possible in European Fundamental Rights Doctrine' (2024) 25(2) *German Law Journal* 185, 200–201.

[253]Recall (n 178) that legally prescribed minimum standards should already be identified in 'M' of the XLRM.

[254]Robert J Lempert and Sara Turner, 'Engaging Multiple Worldviews With Quantitative Decision Support: A Robust Decision-making Demonstration Using the Lake Model' (2021) 41(6) *Risk Analysis* 845.

[255]Brandon L Garrett, 'Applause for the Plausible' (2014) 162(1) *University of Pennsylvania Law Review Online* 221, 227.

[256]Bongiovanni, Sartor and Valentini (eds) (n 204); Silvia Zorzetto, 'Reasonableness' (2015) 1(1) *The Italian Law Journal* 107.

[257]'Reasonable', *Black's Law Dictionary* (6th edn, West Publishing Co 1990) 1265.

[258]Toulmin (n 42).

minds may differ'.[259] Reasonableness is a normative concept when directed at retrospective assessment of the 'correctness' of human judgements, but it can also be used prospectively, as a regulative idea.[260] In keeping with DMDU's focus on the future, we will first consider how to reconceptualise reasonableness as a regulative idea, before considering retrospective assessment of decisions made using DMDU analyses.

Reasonableness as a regulative idea requires two things. First, all potentially relevant factors involved in answering a practical question must be considered.[261] This highlights the importance of XLRM and the first relevance test identified earlier. Second, these factors must be combined in a way that justifies the making of a judgment or decision.[262] Some sort of balancing exercise is integral to this second step, but how to conduct this balancing is left open,[263] not easily answered by clear rules[264] or practices.[265] This highlights the role of the second relevance test identified earlier and the crucial choice of robustness metric. A prospective test of reasonableness could therefore require decision-makers to explicitly identify: (1) the policy pass/fail thresholds of most interest to them, and (2) the robustness metric relied upon, or (less technically) what policy goals are considered most important in the inevitable trade-offs involved in reaching a decision. Recalling the 'overt act' that crystallises a legal decision, these two antecedent conclusions could be recorded in writing in some legal instrument of decision.[266]

In addition, law could incorporate several other reasonable design safeguards to justify the making of DMDU-assisted decisions. For example, a preliminary 'rule of reason' could determine whether DMDU analysis is required in the circumstances of a particular decision.[267] Meanwhile, reasonable constraints could be imposed on DMDU analysts. Law already recognises countless classes of expert[268] and imposes numerous expertise- or experience-based reasonable standards.[269] This could extend to the

[259]Hart (n 73) 661, 664.
[260]Alexy (n 226) 7.
[261]Ibid.
[262]Ibid.
[263]Ibid 10.
[264]Sunstein (n 31); Hart (n 73).
[265]eg, Laudan (n 224) 317–324.
[266]Cf, 2024 amendments to the US NEPA required reporting on, variously, 'reasonably foreseeable' effects, a 'reasonable range of alternatives', including a 'no action' alternative, and 'low probability, high impact' events: 42 US Code § 4332(C) and 40 CFR §§ 1500–1508, 1502.21 (2024).
[267]For example, as often the case with environmental impact assessments: *Marsh v Oregon Natural Resources Council* 490 US 360, 373–374 (1989); *Department of Transportation v Public Citizen* 541 US 752, 754, 767–769 (2004); 40 CFR § 1502.21 (2024).
[268]For example, law's procedures for 'Certifying the Expert': Jasanoff (n 52) 58–61.
[269]For example, Hart (n 73) 660–661; 42 US Code § 4332(D) and 40 CFR §§ 1502.21, 1506.6 (2024), requiring 'the professional integrity, including scientific integrity' of an 'environmental document'.

'reasonable DMDU analyst', as a new or existing class. DMDU practitioners are increasingly professionalised[270] and DMDU methods are already being used in otherwise heavily regulated industries.[271]

Reasonableness could also be used to retrospectively assess decisions made using DMDU analysis. Such reasonable standards are often imprecise mantras,[272] rather than well-defined tests.[273] We should therefore avoid burdening the old workhorse with 'ineffable gradations of probability'.[274] But by definition, no standard of 'proof' can apply to decisions about the future, let alone modelled futures[275] and especially not under deep uncertainty. This makes standards like 'beyond reasonable doubt' or 'more likely than not' useless. Lesser administrative standards may be appropriate,[276] but a single general standard may prove elusive, given diversity in robustness metrics and DMDU methods.[277] Meanwhile, there is a risk that a court dismisses a DMDU analysis as a 'crystal ball inquiry'[278] or 'hypothesizing … events that never in fact occurred. Such an enterprise is not factfinding, but closer to divination'.[279] The DMDU community should expect such judicial scepticism in any litigation challenging a legal decision supported by DMDU analysis, which could foreseeably arise in administrative law or judicial review.[280] We suggest any such judicial scepticism could be overcome by reconceptualising reasonableness, with humility,[281] honesty and transparency,[282] in circumstances where deep uncertainty renders DMDU analysis necessary. Where a court finds itself grappling with how to give substantive effect to reasonableness in such circumstances,[283] robustness seems essential. Rather than a single 'optimal' policy, a 'robust' policy is consistent with the ultimate aim of all reasonable standards: (1) to ensure appropriate precautions are taken, while (2) ensuring that these do not come at too great a cost to other respectable interests.[284]

[270]For example, some DMDU analysts voluntarily commit to a general 'Code of Conduct': Reed and others (n 208) ix.
[271]E.g. water, power, energy, transport, telecommunications and waste: Stanton and Roelich (n 36)
[272]See, e.g. Garrett (n 255) 227–229.
[273]Laudan (n 224) 324.
[274]*United States v Dominguez Benitez* 542 US 74, 86 (2004)(Scalia J, concurring) ('*Dominguez*').
[275]Oreskes, Shrader-Frechette and Belitz (n 101); Stainforth (n 37) 39; Reed and others (n 208) 5–6.
[276]Jasanoff (n 52) 10.
[277]Kwakkel and Haasnoot (n 188) 359–360.
[278]*Scientists' Institute for Public Information v Atomic Energy Commission* 481 F2d 1079 (DC Cir 1973).
[279]*Dominguez* (n 274) 87.
[280]E.g., *Associated Provincial Picture Houses Ltd v Wednesbury Corp* [1948] 1 KB 223; *Sierra Club v Federal Energy Regulatory Commission* 867 F3d 1357, 1368, 1380 (DC Cir 2017); 5 US Code § 706.
[281]Jonas (n 43) 21–22; Jasanoff (n 43).
[282]Oreskes, Shrader-Frechette and Belitz (n 101); Stainforth (n 37) 39–40, 46.
[283]Alexy (n 226) 13–15.
[284]Hart (n 73) 663.

5. Discussion and conclusion: uncharted waters for 'law-and-DMDU'?

This article has theorised a conceptual framework for integrated 'law-and-DMDU' navigational devices for anticipatory governance in the Anthropocene. The following discussion is guided by the question: how could law and exploratory computer modelling tools be further integrated within existing frameworks of anticipatory governance? This will involve looking beyond law to consider broader institutional settings and some of the barriers to and potential pitfalls of further integration. These are summarised in the following five points.

First and foremost, more work needs to be done to overcome existing cultural divides. Scholars regularly identify a failure to pass the baton between two cultures, such as between the natural and the social sciences.[285] Here there is a clear gap between law and governance on the one hand, and DMDU on the other.[286] Few lawyers seem aware that the DMDU community exists.[287] For their part, members of the DMDU community appear to lack understanding about law and governance, and relevant institutional, organisational and individual contexts.[288] This article sought to address that gap and begin to build bridges of understanding between these previously parallel fields, using the 'four Rs'. However, this contribution can only make a modest improvement in mutual awareness and understanding. Additional valuable perspectives could come from considering 'law-and-DMDU' on a more systemic scale,[289] or on the basis of alternative legal principles, or in particular legal contexts.[290] While this analysis suggests that DMDU is an emerging technology that is consistent with existing patterns of anticipatory governance, future work could investigate more practical barriers to further integration. For example, insights from sociology and science & technology studies[291] suggest future research could investigate knowledge production practices and social dynamics within the DMDU community, and the institutional settings in which it operates.

Second, while many scholars refer to vivid metaphorical imagery, it is not at all clear if DMDU practitioners, policymakers and diverse publics share any such common vision. While some computer modellers view themselves as 'cartographers' enabling decision-making by policymakers as

[285]Malm and Hornborg (n 19) 66; Beckert and Bronk (n 46).

[286]Popper (n 41) 384–385.

[287]Sunstein (n 31); Weisbach (n 31); cf Farber (n 31).

[288]Timothy F Malloy and others, 'Advancing Alternative Analysis: Integration of Decision Science' (2017). 125(6) *Environmental Health Perspectives* 66001; Stanton and Roelich (n 36).

[289]For example, Viñuales (n 124); Kotzé and Kim (n 122); Leach (n 4).

[290]For example, the Society for DMDU has established 'Special Interest Groups' in the following sectors: defence and critical infrastructure security; transport and urban systems; and health.

[291]Aykut, Demortain and Benbouzid (n 2).

‘navigators’,[292] the reality is that model outputs are often politicised.[293] Maps can be gerrymandered and the right to navigate is contested. The problems do not go away by mixing metaphors. DMDU proponents claim that their tools and techniques offer a ‘prosthesis’ for the imagination.[294] But even if that is the case, intensive ‘occupational therapy’[295] is required for the human beneficiaries of this technology. DMDU tools remain computationally expensive, methods have a high learning curve, and development costs can be prohibitive.[296] Furthermore, the visualisation and public communication of DMDU results remain significant practical challenges.[297] In short, if DMDU-style exploratory modelling is to remain policy relevant, more needs to be done to improve basic public understanding of DMDU, how it works and where it could be applied. This reinforces the previous point about bridging the cultural divide. In addition, law and governance scholars could contribute by managing public expectations away from ever-improving predictions,[298] and by reimagining how societies could make something of alternative possible futures through systematic, (re)iterative deliberation about available options.[299] New social norms must be developed to use models in such an exploratory way.[300] This would help societies keep track of critical uncertainties, the plausibility of long-range visions, undesirable trajectories, and key social actors or intervention points.[301] The ‘four Rs’ principles in this article offer one of many possible theoretical ways forward.

Third, assuming these broader cultural and social divides can be overcome, existing regulatory frameworks would need to be adapted. While this article has argued that a reinvention of existing principles could help in that task, it is not necessary to reinvent the wheel. Regulators typically follow one of three approaches when confronted with new technology: analogy, categorisation, or new categorisation.[302] Even where a new categorisation occurs, regulation does not emerge from a vacuum because neither new legal paradigms,[303] nor new environmental principles[304] fall from the

[292]Edenhofer and Kowarsch (n 17); Grunwald (n 16).
[293]Andrea Saltelli and others, ‘Five Ways to Ensure that Models Serve Society: a Manifesto’ (2020) 582(7813) *Nature* 482, 483.
[294]Lempert, Popper and Bankes (n 18) xii–xiv.
[295]Toulmin (n 42) 93, 153–154.
[296]Lempert (n 36) 43–44.
[297]Reed and others (n 208) 53; Antonia Hadjimichael and others, ‘Scenario Storyline Discovery for Planning in Multi-actor Human-natural Systems Confronting Change’ (2024) 12(9) *Earth’s Future*.
[298]Stainforth (n 37).
[299]Toulmin (n 42) 93, 153–154.
[300]Saltelli and others (n 293).
[301]Raskin (n 18).
[302]Elen Stokes, ‘Recombinant Regulation: EU Executive Power and Expertise in Responding to Synthetic Biology’ in Maria Weimer and Anniek de Ruijter (eds), *Regulating Risks in the European Union: The Co-Production of Expert and Executive Power* (Hart Publishing 2017).
[303]Leach (n 4).
[304]Stokes (n 4) 921–922.

sky. In adapting existing governance arrangements, regulators are highly likely to 'hew to existing purposes'.[305] There is already substantial overlap between the basic design pattern of iterative DMDU assessment cycle introduced in Section 3, and familiar design patterns in regulatory frameworks for impact assessment.[306] Nevertheless, further adjustments would be required in light of complex existing regulatory frameworks. For example, in the European Union, a DMDU-driven impact assessment of any new regulation would be subject to various existing constraints. These include prescriptive 'rules' for how to formulate, inter alia, the 'logic of intervention',[307] different 'policy options' and 'policy instruments',[308] 'relevant' data,[309] and 'robust' results.[310] While some of these criteria could be readily extended to accommodate DMDU techniques, others would need to be adapted, such as the policy option/instrument 'Tools', since policy options can be generated inductively in some DMDU analyses. In any event, the four theoretical 'lodestars' considered in this article could be used to adapt such existing rule-based guidance, or develop new rules in line with these existing and widely accepted principles.

Fourth, DMDU is not immune to existing concerns about responsibility in algorithmic decision-making.[311] In any appeal against a DMDU analysis, no court could order algorithm or analyst to 'peer beneath the hood and easily explain in granular detail'[312] how the algorithm 'decided' between millions of possible combinations of model inputs.[313] While this is somewhat mitigated by the transparency of basic relationships identified in the XLRM matrix, the critique rings true for 'black box' algorithmic decision-making in scenario discovery and robustness analysis. However, we should be clear-eyed about our expectations of algorithmic responsibility; algorithms give 'partial, contingent, oblique, incomplete, and ungrounded' accounts of themselves all the time, but so too do humans.[314] Ultimately, such ethical concerns should be considered against the multiple human intervention points and reiteration in DMDU methods.

Finally, we must acknowledge the effect of legal and political uncertainty. While regulatory impact analysis is typically shown deference in judicial

[305]Rachel E Salcido, 'Rationing Environmental Law in a Time of Climate Change' (2014) 46 *Loyola University of Chicago Law Journal* 617, 661–663, footnote 252.
[306]Wernick (n 23).
[307]For example, European Commission (n 28) Tools #11, 46, 67.
[308]Ibid Tools #16–17.
[309]For example, ibid Tool #4, but 'relevant'/'relevance' appears repeatedly throughout the Toolbox.
[310]For example, ibid Tool #65, but 'robust'/'robustness' appears repeatedly throughout the Toolbox.
[311]O'Neil (n 77); Bayamlıoğlu and Leenes (n 77); Louise Amoore, *Cloud Ethics: Algorithms and the Attributes of Ourselves and Others* (Duke University Press 2020).
[312]Mustafa Suleyman, *The Coming Wave* (Random House UK 2024) 114.
[313]Amoore (n 311) 14.
[314]Ibid.

review,[315] the *Loper Bright Enterprises* decision of the US Supreme Court and backlash to the European Green New Deal provide pause for thought. In the US context, the *Loper Bright Enterprises* decision shifts attention to judicial knowledge and understanding of computer models in modern regulatory practice, particularly in regulatory impact assessment. For this reason, this article went back to first principles in anticipation of a judicial audience in imminent need of understanding exploratory modelling techniques such as DMDU. Meanwhile, in the EU, the backlash to the European Green New Deal appears to have prompted reflexivity about its existing anticipatory practices.[316] A particular focus appears to be the development of 'frameworks for decision-making under deep uncertainty'.[317] The iterative cycle envisaged by DMDU appears to offer one such framework and a promising way forward. For all these reasons, this article calls for lawyers and legal scholars to familiarise themselves with the DMDU community, and their tools and techniques for exploratory modelling under deep uncertainty.

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[315]Patricia Popelier, 'L'analyse d'impact de la réglementation: une perspective juridique [A Legal Perspective on Regulatory Impact Assessments]' (2018) 35(3–4) *Politiques et Management Public* 107, 116–117; cf *Loper Bright Enterprises v Raimondo* (n 1).
[316]See, for example, the EU's Horizon Europe project CAPABLE (ClimAte Policy AcceptaBiLity Economic framework) grant agreement No 101056891 https://capableclimate.eu/about/.
[317]Ibid.