DECISION SUPPORT TOOLS *for* COMPLEX DECISIONS UNDER UNCERTAINTY

A publication of the **Analysis Under Uncertainty *for* Decision Makers Network.**

AU4DM Network

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A PUBLICATION OF THE
ANALYSIS UNDER UNCERTAINTY for DECISION MAKERS NETWORK

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The **Analysis Under Uncertainty for Decision Makers Network** (AU4DM) is a community of researchers and professionals from policy, academia, and industry, who are seeking to develop a better understanding of decision-making to build capacity and improve the way decisions are made across diverse sectors and domains.

For further details about the network, visit
http://www.au4dmnetworks.co.uk/.

AU4DM Network

Warwick Statistics

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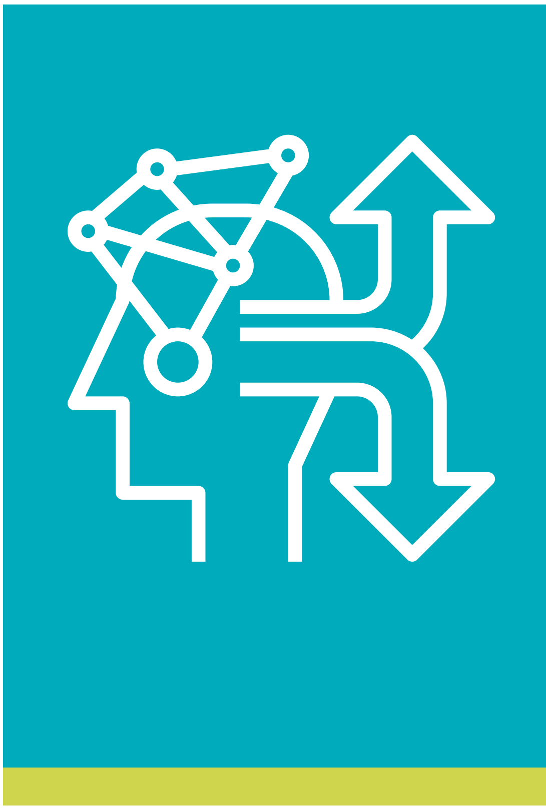
1 DECISION SUPPORT TOOLS
AN INTRODUCTION

An issue continually arising at meetings of the AU4DM network is the need among analysts, advisors and decision-makers in our community—and, we guess, beyond!—for some guidance on the tools and methods out there which support complex decisions in the face of uncertainty. This is far from easy because there are many tools and, worse still, they are buried in a mire of inconsistent terminology. Nonetheless, we have taken up the challenge and, despite knowing that any serious guidance would need a textbook or two, we have pulled together this short booklet. The early sections set the context, or rather contexts, for decision-making, particularly focusing on the types of uncertainties that decision-makers may encounter. We note that there are many competing methodologies, some having foundations that are inconsistent with others. We also describe the decision-making process though not in great detail, before providing a catalogue, giving a brief description of each tool, providing one or two key references and, where possible, point to a case study. We also provide two graphics: one relating the various tools to the decision-making process, the other relating them to the type of uncertainty faced.

Please note that this is a living document, now in its second edition. It will evolve with your feedback. If you have any comments, please contact us via the website[1]. In particular, if you notice an omission, please let us know. We would like to extend the catalogue to cover those tools and methods that you are interested in



[1] *http://www.au4dmnetworks.co.uk/contact-us*

2 CATEGORISING UNCERTAINTY FOR DECISION-MAKING

Uncertainty comes in many different forms. If for our purposes we take uncertainty as something defined by the questions we ask during deliberations on what to do, we may recognise the following.

- **Stochastic uncertainties** *(physical randomness and variations), e.g.*
  - Will the next card be an ace?
  - Will there be a serious storm or earthquake in Europe next year?
  - What proportion of car batteries will fail in the first year of use?
- **Epistemological uncertainties** *(lack of knowledge), e.g.*
  - What is happening?
  - What can we learn from the data?
  - What might our competitors do?
  - How good is our understanding of the causes of this phenomenon?
- **Analytical uncertainties** *(model fit and accuracy), e.g.*
  - Do we have enough data to make a good decision?
  - How well do we know the model parameters?
  - Have we chosen the right model for our context?
  - How accurate are the calculations, given approximations made for tractability?
  - How well does that model fit the world?
- **Ambiguities** *(ill-defined meaning), e.g.*
  - What do we mean by 'normal working conditions' for a machine?
  - What do we mean by 'human error'?
  - What do we mean by a 'high' risk?
- **Value uncertainties** *(ill-defined objectives), e.g.*
  - How much should the NHS pay for a specific medicine?
  - What weight should we put on this objective relative to others?
  - What is the right — ethical — thing to do?

We have labelled five categories of uncertainty above. We could have easily have used a finer categorisation, since uncertainties can be very varied, differing in many qualities. But five will serve here. It should be apparent that stochastic, epistemological and analytical uncertainties might be addressed by modelling, data analysis and drawing in scientific and other expertise. They relate to questions about the external world. On the other hand, ambiguities and value uncertainties are of a different character. Many authors, particularly in the scientific literature, do not include these as categories of uncertainties in the senses that we have here. We do so simply because many decision-makers and stakeholders, when asked about their uncertainties, immediately refer to such concerns. These do not reflect external uncertainties, but the decision-makers' internal ones. To resolve those, they will need to reflect and think through their position more carefully.

There are tools to help in all cases, but as with all toolboxes, one needs to select the right tool for the specific uncertainty. Generally, decision tools which model uncertainty, usually with probabilities, tend to focus on exploring and understanding the implications of stochastic, epistemological and analytical uncertainties. Tools which explore trade-offs between multiple criteria (also commonly referred to as attributes or objectives) tend to be used to stimulate discussions addressing ambiguity and value uncertainties, and to find socially or politically acceptable alternatives.

David Snowden developed another categorisation of uncertainty called *Cynefin,* a Welsh word for habitat and used here to describe the context for a decision, categorises knowledge relative to a specific decision. Cynefin roughly divides decision contexts into four spaces: see Figure 1. In the ***Known Space,*** also called *Simple* or the *Realm of Scientific Knowledge,* relationships between cause and effect are well understood, so we will know what will happen if we take a specific action. All systems and behaviours can be fully modelled. The consequences of any course of action can be predicted with near certainty. In such contexts, decision-making tends to take the form of recognising patterns and responding to them with well-rehearsed actions, i.e. recognition-primed decision-making. Such knowledge of cause and effect will have come from familiarity. We will regularly have experienced similar situations. That means we will not only have some certainty about what will happen as a result of any action, we will also have thought through our values as they apply in this context. Thus, there will be little ambiguity or value uncertainty in such contexts.

In the ***Knowable Space,*** also called *Complicated* or the *Realm of Scientific Inquiry*, cause and effect relationships are generally understood, but for any specific decision further data are needed before the consequences of any action can be predicted reliably. The decision-makers will face epistemological uncertainties and probably stochastic and analytical ones too. Decision analysis and support will include the fitting and use of models to forecast the potential outcomes of actions with appropriate levels of uncertainty. Moreover, although the decision-makers will have experienced such situations before they may be less sure of how their values apply and will need to reflect on these in making the final decision.

In the ***Complex Space,*** also called the *Realm of Social Systems,* decision-making faces many poorly understood, interacting causes and effects. Knowledge is at best qualitative: there are simply too many potential interactions to disentangle particular causes and effects. There are no precise quantitative models to predict system behaviours such as in the Known and Knowable spaces. Decision analysis is still possible, but its style will be broader, with less emphasis on details, and more focus on exploring judgement and issues, and on developing broad strategies that are flexible enough to accommodate changes as the situation evolves. Analysis may begin and, perhaps, end with much more informal qualitative models, sometimes known under the general heading of soft modelling or problem structuring methods. Decision-makers will also be less clear on their values and they will need to strive to avoid motherhood-and-apple-pie objectives, such as minimise cost, improve well-being or maximise safety.

Contexts in the ***Chaotic Space*** involve events and behaviours beyond our current experience and there are no obvious candidates for cause and effect. Decision-making cannot be based upon analysis because there are no concepts of how to separate entities and predict their interactions. The situation is entirely novel to us. Decision-makers will need to take probing actions and see what happens, until they can make some sort of sense of the situation, gradually drawing the context back into one of the other spaces.

The central blob in Figure 1 is sometimes called the ***Disordered Space.*** It simply refers to those contexts that we have not had time to categorise. The Disordered Space and the Chaotic Space are far from the same. Contexts in the former may well lie in the Known, Knowable or Complex Spaces; we just need to recognise that they do. Those in the latter will be completely novel.

Figure 3 on page 27 categorises the decision tools against the Cynefin spaces for which their support is the most appropriate.

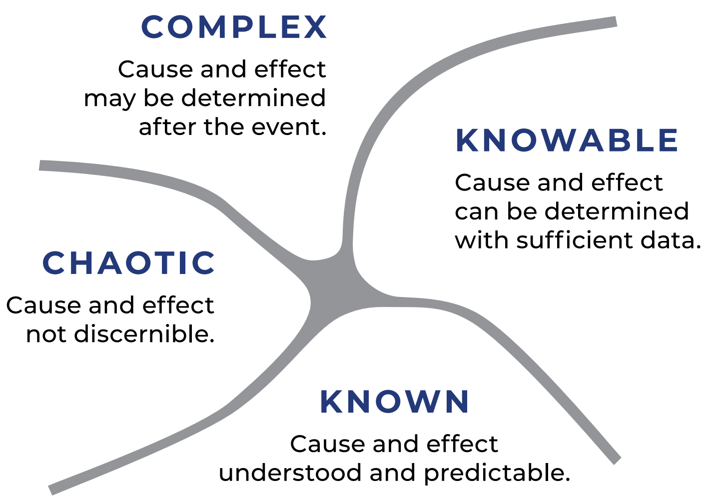
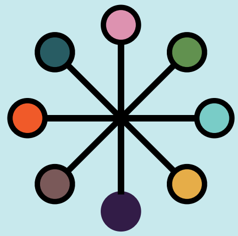


Figure 1: Cynefin (see www.cognitive-edge.com)

3 DECISION ANALYSIS METHODOLOGIES AND TERMINOLOGIES

Decision analysis is a set of methodologies and tools, building on many theories and practices developed in many disciplines. Within it, there are many schools and approaches, some pragmatic, others with very strong, often constraining theoretical foundations. Each makes its own distinct assumptions about the decision-making process and usually how alternatives should be evaluated. Here we can only provide the briefest of surveys. Note that our broad categories are far from mutually exclusive. We have been referring to methodologies and tools. The former refers to the broad theory of how decisions should be made and how analysts can best support them. The latter refers to particular techniques or software that implement the methodology in specific circumstances. We use techniques and methods as synonyms for tools.

Here we identify eight very broad categories of tools that will help to bring some order to the lists and plots later on. Beware the distinctions between these categories are nebulous, and many might classify tools differently.



BAYESIAN METHODS

(SHADED PINK)[2]

Once the ugly duckling of statistics, these methods have developed into the largest, most coherent family of methods for statistical, risk and decision analysis. Underpinned by firm theoretical and methodological bases and new, powerful computational methods, they are used for large complex problems, e.g. environmental and technical risk management. They lie at the heart of many machine learning and artificial intelligence algorithms. They can also be used interactively in small groups to explore strategic issues that focus on the 'big picture'. Intuitive, graphical interfaces such as decision trees, belief nets and influence diagrams hide the mathematics, while exhibiting the key interactions in models. Bayesian approaches break down problems so that:

- the majority of stochastic, epistemological and analytical uncertainties can be modelled practically, and arguably all of them conceptually, using probabilities;
- data can be analysed and the understanding incorporated seamlessly into the overall analysis of a problem;
- expert judgement may be used when data are not available;
- conflicting values about complex outcomes can be debated and explored before risk and uncertainty are taken into account.

[2] Each broad category of methodologies and tools is indicated in a different colour in the catalogue(pp 12-25) and in Figures 3 and 4.

INTERVAL METHODS

(SHADED GREEN) ■

Many worry that decision-makers, their advisors and their experts cannot give numerical values sufficiently accurately for the results of any fully precise analysis to be justified. So a multitude of approaches have been suggested which give ranges for their numerical inputs: e.g. interval arithmetic, fuzzy mathematics, rough sets, belief functions, and multimodal logics. While their motivation is both understandable and laudable, weakening the arithmetic also weakens some of the other foundational assumptions of methods. In doing this they fail to enforce one or more basic principles of rationality or lose the possibility of defining some of the components operationally. Thus some interval methods may only be justified on pragmatic grounds, if at all.

MULTI-CRITERIA DECISION ANALYSIS (MCDA)

(SHADED LIGHT BLUE) ■

A term covering a vast range of techniques: e.g. multi-criteria value modelling, interactive multi-objective decision-making, multi-attribute value analysis and the analytical hierarchical process. Generally, these eschew dealing with stochastic, epistemological or analytical uncertainties up front and focus on modelling and exploring conflicting objectives and balancing these. Some do address stochastic and epistemological uncertainties; and, indeed, Bayesian multi-attribute value and utility techniques can be classified as MCDA. These techniques are especially useful in working with senior decision-makers in setting policy and broad objectives, and in processes of stakeholder engagement. Understanding the objectives in dealing with an issue and setting broad strategy provides sound foundations to an analysis, communication with all stakeholders and opportunities for collective deliberative decision-making.

OUTRANKING METHODS

(SHADED GOLD) ■

These methods derive from a French philosophical tradition and seek first to display as much as can be deduced 'objectively' in a problem, before introducing any subjective evaluation such as putting weights on different objectives. It would be easy to classify them as 'just another' MCDA method, but they have deeper philosophical and mathematical foundations than many other MCDA methods.

DECISION-MAKING UNDER DEEP UNCERTAINTY (DMDU)

(SHADED PURPLE) ■

In one sense this is a relatively recent movement though it stems from a distinction made in 1921 by Frank Knight between risk and uncertainty. In situations of risk, he argued, probability can be used to model what is not known about the future. In situations of (strict) uncertainty, too little is known for probability to be used at all and the uncertainty is so great that it cannot be modelled quantitatively. The distinction was explored further in the early 1950s, stimulated in part by the development of game theory leading to *maximin* methods that minimised the worst that could happen. In recent years, strict uncertainty has been renamed *deep uncertainty*, now defined more clearly as circumstances in which data are too sparse, experts in too much disagreement or time is too short to model the uncertainty. Some of the work in this area is very thought-provoking, leading to, for example, *scenario-focused decision analysis*.

SOFT ELICITATION

(SHADED BROWN) ■

Soft elicitation is the process of asking problem owners for the knowledge, perceptions, beliefs, uncertainties and values that a model needs to embody before being populated with numbers. Many disciplines have thought about soft elicitation, but with differing terminologies and little cross-fertilisation: e.g. mathematicians refer to model building; decision analysts and operational researchers to soft OR and problem structuring; risk analysts to optioneering and hazard analysis; statisticians to exploratory data analysis, Bayesian elicitation and structural learning; knowledge engineers to knowledge elicitation, sense-making, creativity and innovation; and information systems engineers to soft systems. We should emphasise one aspect of soft elicitation: *value-focused thinking*. This emphasises the importance of ensuring that the problem owners are clear on their objectives at the outset of the process. Doing so turns out to encourage far more creative problem solving than focusing on a list of possible options and also ensures that value uncertainties are addressed. Soft elicitation techniques can be very powerful, catalysing much discussion and building clarity. Sometimes they are all that is needed for the decision-makers to see a way forward. Otherwise, and more usually in complex problems, they provide an excellent basis on which analysts can build their quantitative models.

ECONOMIC AND FINANCIAL APPROACHES

(SHADED RED)

Much business, industrial and governmental decision-making involves costs and financial income; so it is not surprising that many of the tools involved in analysing decisions stem from economic theory and accounting practices. Indeed, cost benefit analysis, which seeks to price out all aspects of the consequence of a strategy, is one of the older tools used across government and still holds sway as *the* decision tool of choice in many government departments. Some might include many Bayesian tools under the heading of economic tools since the concept of rational economic man, which was introduced in economics in the late 19th and early 20th centuries, relates closely to the rationality embodies in the Bayesian paradigm. However, Bayesian approaches pay much more attention to addressing actual rather idealised behaviour than is common in economic and financial approaches.

We should note three 'disciplines' that are broader than any of these methodologies. ***Statistics*** is a well-known family of methodologies and tools for investigating uncertainty and drawing inferences from data. ***Operational Research*** (OR)[3] is similarly well known as a family of methodologies and tools for improving and optimising processes in industry, business, government and society. OR was described for many years by the UK OR Society as the 'Science of Decision-making' so it is not surprising that many look to OR for decision support tools. Many of these, such as linear programming, are deterministic and do not fit into this catalogue. But we do note that deterministic tools can be used in sensitivity analysis (see below). Finally, ***Analytics*** is a relatively modern term that covers the application of both Statistics and OR, usually in the context of 'Big Data'.

Whatever decision support tool is used, if it makes any calculations, then sensitivity analysis is important. Very seldom are the numbers we use agreed and specified precisely. Sensitivity analysis checks whether the implication of the analysis—usually a pointer to the optimal action or a ranking of available actions—depends on some spurious accuracy in the inputs. Decision-makers generally do not want to base their decisions on a marginal difference in the fourth decimal place! Sensitivity analysis can discover the robustness of the decision to minor changes in the inputs. Moreover, the process of sensitivity analysis, especially when performed with the decision-makers, their advisors or stakeholders present, can be very helpful in articulating discussion and surfacing important differences of opinion. The focus of sensitivity techniques is on the numbers used in the models and analysis. We should also check for the robustness of the conclusions to the choice of models used to predict the consequences of various possible decisions. There is seldom unanimous agreement among modellers on the software to use in consequence modelling. Although the same scientific knowledge may lie at the heart of different software, it may have been encoded with different assumptions and approximations to make the calculations computationally feasible.

DECISION PROCESS MANAGEMENT

(SHADED PETROL-BLUE)

The process of decision-making can be very complex, extending over time and involving many parties. A range of tools and techniques have grown up to help manage the decision-making process and they have inevitably expanded in function to support, at least in some sense, the decision-making itself, even though their primary focus might be on, say, implementation and monitoring risks.

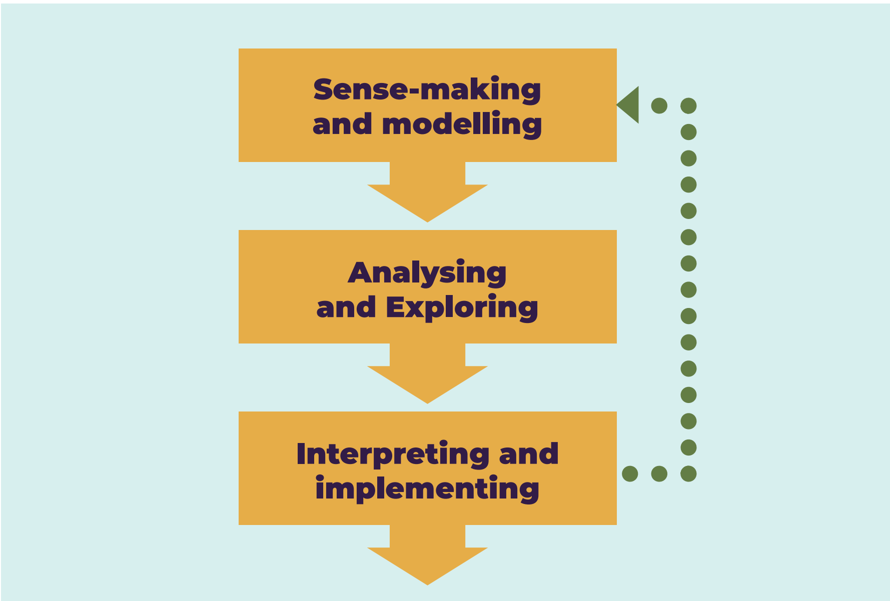


Figure 2: The Decision-Making Process

[3] Operations research in the U.S.A.

4 SYSTEM 1 THINKING VERSUS SYSTEM 2 THINKING

Each methodology makes some assumptions about how decisions should be made rationally — soundly, if you prefer. There is, therefore, a natural question about whether a decision-maker left to his or her own devices would choose in such a way. Unfortunately, the answer is: not consistently. Behavioural studies have identified many 'heuristics and biases', though this rather pejorative terminology does depend on ones perspective. Currently one talks of system 1 and system 2 thinking, the former referring to instinctive thought on the fringes of consciousness, the latter to more conscious, explicit, analytic patterns of thought.

Decision analysis encourages system 2 thinking, helping decision-makers, their advisors and stakeholders think through and reflect on the issues. Their arguments become explicit and auditable for consistency and rationality. In discussions and specifically in articulating probability and value judgements, participants are likely to resort to system 1 thinking and be unaware of the full implications of their heuristics and potential variations in their judgements across different contexts. Better methodologies and tools have processes for nudging participants to think carefully and explicitly when giving numeric judgements, but weaker ones simply take numerical responses and use them in the calculations. The notion of 'garbage in; garbage out' applies just as much to judgemental as empirical data.

5 THE DECISION-MAKING PROCESS

Few decisions are a matter of simply evaluating options and choosing one. Firstly, you have to understand the context and the issues faced, bounding the problem. Then you need to identify what you are trying to achieve, i.e. define objectives, and formulate options. This stage should encourage divergent thinking to ensure as much as possible that 'all bases are being covered.' Only then, can you analyse and explore each option's pros and cons. Here thinking is convergent as the analysis eliminates some options and focuses attention on optimal or at least robust ones leading to a decision. Even when the decision is made, you have to think through how to interpret, present and implement your choice. In many, arguably most decisions the process iterates, as one part of the process prompts you to reflect and revise earlier parts. The iterations stop when the decision-makers judge that nothing more will be gained by further analysis. They feel that the modelling and analysis are sufficient — we shall say requisite — for their purposes. Each of these three broad stages can be broken down into more detailed steps, though we shall not do so here. With the caveat that these processes are much more interlinked and iterative in reality, we shall take Figure 2 as providing an overview of the stages in decision-making. In Figure 4 on page 29, we use this overview of the decision-making process to indicate where different tools in this catalogue might be used most effectively.

Not all decision analyses pass through these phases. In well-rehearsed cases, e.g. operational decisions, issues are well understood and formulation and interpretation need less emphasis. More complex tactical and strategic decisions, perhaps with novel aspects, require more careful exploration, formulation and, subsequently, interpretation during implementation.

For many complex decisions, current practice, particularly in the public sector, is to consult and engage with stakeholders throughout the three stages of the decision-making process. Many of the decision support tools listed here have proved their worth in articulating such discussions.

6 A BRIEF BIBLIOGRAPHY ON DECISION-MAKING

The above sections have provided the briefest of introductions to Decision Science. Since decision-making is a key characteristic of human behaviour, its study has been central to many disciplines ranging from philosophy through economics, environmental science, psychology, political and business studies to management science, operational research and statistics. So in writing this, we have probably raised more questions than we have answered. Much more extensive introductions to and discussions of the issues may be found in the following.

1. **Belton, V. and T. J. Stewart** (2002). *Multiple Criteria Decision Analysis: an Integrated Approach.* Boston, Kluwer Academic Press.

   Many decision analysis methods and tools hardly address uncertainty at all. Their focus is on conflicting objectives and how these might be traded-off in coming to a balanced decision. This book surveys many of these, setting the discussion in a careful presentation of the decision-making process.

2. **Burgman, M. A.** (2015). *Trusting Judgements: How to Get the Best Out of Experts,* Cambridge, Cambridge University Press.

   Whenever possible, decision-making should be grounded in data; but that is not always possible. Despite the promises of 'big data' and the analytics movement, for many decisions, e.g. those dealing with novel risks and opportunities or managing highly complex systems, there are few if any relevant data. In such cases, decision-making relies on input from experts. This book both motivates the use of expert judgement and surveys what we know about how to draw in expertise in a rational, auditable manner.

3. **French, S., A. J. Maule and K. N. Papamichail** (2009). *Decision Behaviour, Analysis and Support.* Cambridge, Cambridge University Press.

   A text-book written for final year undergraduates, masters and MBA students, but one that hides almost all the mathematical underpinnings. It draws together perspectives from decision theory, psychology, behavioural science, management and information systems to provide a multi-disciplinary overview of decision-making and how we might support it. In particular, it emphasises the importance of value-focused thinking and requisite modelling.

4. **Morgan, G. M. and M. Henrion** (1990). *Uncertainty: a guide to dealing with Uncertainty in Qualitative Risk and Policy Analysis.* Cambridge, Cambridge University Press.

   A classic text on dealing with uncertainty: still available and still relevant. The authors explain the ways in which uncertainty is an important factor in the problems of risk and policy analysis. They discuss the source and nature of uncertainty, techniques for obtaining and using expert judgment, and review a variety of simple and advanced methods for analysing uncertainty. The writing is technical in places, but the text is broadly accessible to many audiences.

5. **Gregory, R. S., L. Failing, M. Harstone, G. Long, T. McDaniels and D. Ohlson** (2013). *Structured Decision-making: A Practical Guide to Environmental Management Choices.* Chichester, Wiley-Blackwell.

   Written in a broadly non-mathematical style, this book discusses how tools and methodologies can be used to articulate deliberations between stakeholders, advisors and decision-makers on complex decisions. As the title suggests, their context relates to environmental management, but the ideas have much wider applicability.

6. **Hodgkinson, G. and W. Starbuck**, Eds. (2008). *The Oxford Handbook of Organizational Decision-making.* Oxford, Oxford University Press.

   This collection of readings covers all the issues of context that need to understand for any decision analysis to be effective. A decision analyst needs to understand the organisational pressures and influences playing on the decision-makers. Highly multi-disciplinary, this is essential reading whatever approach to decision analysis is taken.

7. **Kahneman, D.** (2011). *Thinking, Fast and Slow.* London, Penguin, Allen Lane.

   Daniel Kahneman won the Nobel Prize for Economics in 2002 for behavioural studies of decision-making. Working with Amos Tversky, who sadly died before any Nobel prize could be considered, he developed Prospect Theory which is perhaps currently the best description of how we *do* make decisions, as opposed to how we *should*. They and many other behavioural scientists have catalogued many 'heuristics and biases', i.e. pitfalls, that sound, explicit, auditable analyses should help decision-makers avoid. This book is both an excellent introduction to these studies and a delightful autobiography. It deservedly sat for many months in the Sunday Times bestsellers list, showing how accessible his writing is.

8. **Marchau, V., W. E. Walker, P. Bloemen and S. Popper**, Eds. (2019). *Decision Making under Deep Uncertainty,* Cham, Springer.

   A book of readings providing a unified and comprehensive treatment of decision-making in the face of deep uncertainty. The coverage includes many approaches and tools and is supported by clear case studies. It is an open source book, whose publication has been funded by the Society for Decision Making under Deep Uncertainty (***www.deepuncertainty.org***).

9. **Rosenhead, J. and J. Mingers,** Eds. (2001). *Rational Analysis for a Problematic World Revisited.* Chichester, John Wiley and Sons.

   This and an earlier collection of readings survey five soft elicitation methods: strategic options development and analysis (SODA), strategic choice approach, soft systems methodology, robustness analysis, drama theory. Case studies of each are given and much attention is paid to the interactive processes between the analyst and the problem-owners.

10. **Saltelli, A., K. Chan and E.M. Scott**, Eds. (2000). *Sensitivity Analysis.* Chichester, John Wiley and Sons.

    Discusses the methodology and techniques that may be used to explore the sensitivity of model outputs to (small) changes in their numerical inputs. The text does not shy away from the mathematics and remains a key reference on sensitivity analysis in complex modelling.

11. **Spetzler, C. S. and H. Winter** (2016). *Decision Quality: Value Creation from Better Business Decisions,* Hoboken, John Wiley & Sons.

    This book describes the approach to decision analysis developed and applied by the Strategic Decisions Group (SDG) in many consultancy projects. Its focus is more on issues arising in large commercial organisations than in the public or the third sector, but its advice throughout is excellent, well-informed through experience. The book presents decision analysis through six phases to ensure that the deliberation is sound.

12. **Smith, J. Q.** (2010). *Bayesian Decision Analysis: Principles and Practice.* Cambridge, Cambridge University Press.

    For readers wanting a mathematical introduction to the principles of Bayesian Decision Analysis there are few better introductions. The book covers decision trees, belief nets and influence diagrams, key tools in many areas of machine learning as well as in decision analysis itself. It also shows the many connections between statistical inference and decision theory.

7 CATALOGUE OF TOOLS

COLOUR KEY

Bayesian Methods

Interval Methods

MCDA Methods

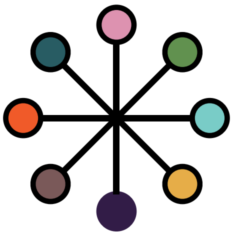
Outranking Methods

DMDU Methods

Soft Elicitation Methods

Economic and Financial Methods

Decision Process Management



This catalogue lists a number of tools and practices identified by members of AU4DM. For each we give a ***very*** brief description, one or two key references to direct users an entry point for further reading, one or two case studies where possible, and cross-reference related tools. Google scholar should lead you to copies of all the references from the details here. We sort the tools according to the methodologies listed on pages 6-8.

We also add a ***Miscellaneous Modelling Tools*** category to include approaches commonly used in decision analysis, but which do have not specific decision modelling elements. The index lists the tools in alphabetical order, if you are searching for information on a specific tool.

BAYESIAN METHODS

ADVERSARIAL RISK ANALYSIS

Def. A recent Bayesian development combining game theory and decision analysis to build tools to advise a decision-maker facing other players, who may be non-Bayesian.

Ref. Banks, D. L., Aliaga, J. M. R. and Insua, D. R. (2015). *Adversarial risk analysis,* CRC Press.

Case Study Sevillano, J.C., Rios Insua, D. and Rios, J., (2012) Adversarial risk analysis: The Somali pirates case. *Decision Analysis,* **9**(2), pp.86-95.

See also Conflict analysis, Game Theory

BELIEF NETS

Def. A Bayesian approach to structuring understanding of conditional dependencies between uncertainties and develop complex probability models.

Ref. Jensen, F. V. (2001). *Bayesian Networks and Decision Graphs.* New York, Springer

Fenton, N. and M. Neil (2012). *Risk Assessment and Decision Analysis with Bayesian Networks.* Boca Raton, CRC Press.

Case Study Chen, S., Huang, W., Chen, M., Zhong, J. and Cheng, J., (2017) Airlines Content Recommendations Based on Passengers' Choice Using Bayesian Belief Networks. In *Bayesian Inference.* IntechOpen.

See also Influence diagrams and Decision Trees

INFLUENCE DIAGRAMS AND DECISION TREES

Def. The basic tools of Bayesian decision analysis which help decision-makers balance their uncertainties with their values and risk attitude to determine a strategy.

Ref. Reilly, T. and R. T. Clemen (2013). *Making Hard Decisions with Decision Tools.* Boston, South Western College Publishing

Abbas, A. E. and Howard, R. A. (2015). *Foundations of Decision Analysis.* Pearson Higher Ed

Case Study Kloeber Jr, J.M., Ralston, B.E. and Deckro, R.F., (2017) Selecting a Portfolio of Technologies: An Application of Decision Analysis. Decision Sciences, **30**, pp.217-236.

See also Belief Nets

MULTI-ATTRIBUTE VALUE THEORY (MAVT) AND MULTI-ATTRIBUTE UTILITY THEORY (MAUT)

Def. Bayesian modelling of preferences and conflicting objectives whether or not uncertainty is present.

Ref. Keeney, R. L. and Raiffa, H. (1993). *Decisions with multiple objectives: preferences and value trade-offs,* Cambridge, Cambridge University Press.

Goodwin, P. and G. Wright (2014). *Decision Analysis for Management Judgement.* Chichester, John Wiley and Sons.

Case Study Schuwirth, N., Reichert, P. and Lienert, J., (2012) Methodological aspects of multi-criteria decision analysis for policy support: A case study on pharmaceutical removal from hospital wastewater. *European Journal of Operational Research,* **220**(2), pp.472-483.

See also Value-focused thinking

STRUCTURED EXPERT JUDGEMENT (SEJ)

Def. A family of methods for working with experts and drawing out their assessment of uncertainties.

Ref. Dias, L., Morton, A. and Quigley, J., Eds. (2017). *Elicitation of Preferences and Uncertainty: Processes and Procedures.* Springer.

Hemming, V., Burgman, M.A., Hanea, A.M., McBride, M.F. and Wintle, B.C., (2018) A practical guide to structured expert elicitation using the IDEA protocol. Methods in *Ecology and Evolution,* **9**(1), pp.169-180.

Case Study Cooke, R.M., Wittmann, M.E., Lodge, D.M., Rothlisberger, J.D., Rutherford, E.S., Zhang, H. and Mason, D.M., (2014) Out-of-sample validation for structured expert judgment of Asian carp establishment in Lake Erie. *Integrated Environmental Assessment and Management,* **10**(4), pp.522-528.

INTERVAL METHODS

DEMPSTER-SHAFER THEORY

Def. Dempster-Shafer theory is a generalised form of belief theory, which builds models that are weaker than probability models but which with further assumptions move consistently towards full probability models.

Ref. Shafer, G. (1976). *A Mathematical Theory of Evidence,* Princeton University Press. Princeton, USA.

Case Study Coppolino, L., D'Antonio, S., Formicola, V., Massei, C. and Romano, L., (2015) Use of the Dempster-Shafer theory for fraud detection: the mobile money transfer case study. In *Intelligent Distributed Computing VIII* (pp. 465-474). Springer, Cham.

See also Evidential Reasoning

EVIDENTIAL REASONING

Def. An approach using Dempster-Shafer Theory to allow for uncertainties in preferences.

Ref. Yang, J.B., Wang, Y.M., Xu, D.L. and Chin, K.S., (2006) The evidential reasoning approach for MADA under both probabilistic and fuzzy uncertainties. *European journal of operational research,* **171**(1), pp.309-343.

Xu, D.L., (2012) An introduction and survey of the evidential reasoning approach for multiple criteria decision analysis. *Annals of Operations Research,* **195**(1), pp.163-187.

Case Study Wang, Y.M. and Elhag, T.M., (2008) Evidential reasoning approach for bridge condition assessment. *Expert Systems with Applications,* **34**(1), pp.689-699.

See also Dempster-Shafer theory

FUZZY DECISION ANALYSIS

Def. There are very many approaches to decision making based on fuzzy mathematics, in which ambiguity is emphasised. Often fuzzy mathematical approaches are built upon other decision methodologies.

Ref. Bellman, R. E. and L. A. Zadeh (1970). "Decision making in a fuzzy environment." *Management Science* **17**(4): B141-B164.

Liu, W. and Liao, H., 2017. A bibliometric analysis of fuzzy decision research during 1970–2015. *International Journal of Fuzzy Systems,* **19**(1), pp.1-14.

Case Study Beskese, A., Demir, H.H., Ozcan, H.K. and Okten, H.E., (2015) Landfill site selection using fuzzy AHP and fuzzy TOPSIS: a case study for Istanbul. *Environmental Earth Sciences,* **73**(7), pp.3513-3521.

ANALYTICAL HIERARCHY PROCESS (AHP)

Def. An MCDA method, used extensively, which askes decision-makers to say whether one element or another is preferred and then deduces a ranking of alternatives.

Ref. Saaty, T. L. (1980). *The Analytical Hierarchy Process.* New York, McGraw-Hill.

Ho, W., (2008) Integrated analytic hierarchy process and its applications–A literature review. *European Journal of Operational Research,* **186**(1), pp.211-228.

Case Study Koç, E. and Burhan, H.A., (2015) An application of analytic hierarchy process (AHP) in a real world problem of store location selection. *Advances in Management and Applied Economics,* **5**(1), p.41.

SIMPLE MULTI-ATTRIBUTE RATING TECHNIQUE (SMART)

Def. SMART is one of the simpler decision analytic tools. It uses simple arithmetic, is quick to use and is transparent, but it does make a host of heroic and dubious assumptions that may not apply in practice.

Ref. Edwards, W. and F. H. Barron (1994). “SMARTs and SMARTER: improved simple methods for multi-attribute utility measurement.” *Organisational Behaviour and Human Decision Process* **60**: 306-325.

Valiris, G., Chytas, P. and Glykas, M., (2005). Making decisions using the balanced scorecard and the simple multi-attribute rating technique. *Performance Measurement and Metrics,* **6**(3), pp.159-171.

Case Study Bray, R., (2015) Developing a participative multi criteria decision making technique: a case study. *International Journal of Management and Decision Making,* **14**(1), pp.66-80.

MULTI-CRITERIA DECISION ANALYSIS (MCDA)

TECHNIQUE FOR ORDER PREFERENCE BY SIMILARITY TO THE IDEAL SOLUTION (TOPSIS)

Def. There are several ideal point MCDA methods, of which TOPSIS is an example. These identify the decision makers' ideal but usually quite infeasible solution and then seek a feasible solution near to this idea.

Ref. Yoon, K.P. and Kim, W.K., (2017) The behavioral TOPSIS. *Expert Systems with Applications,* **89,** pp.266-272.

Zavadskas, E.K., Mardani, A., Turskis, Z., Jusoh, A. and Nor, K.M., (2016) Development of TOPSIS method to solve complicated decision-making problems—An overview on developments from 2000 to 2015. *International Journal of Information Technology & Decision Making,* **15**(03), pp.645-682.

Case Study Özder, E.H., Eren, T. and Çetin, S.Ö., (2015) Supplier selection with TOPSIS and goal programming methods: A case study. *Journal of Trends in the Development of Machinery and Associated Technology,* **19**(1), pp.109-112.

UTILITY ASSESSMENT (UTA)

Def. A method based on MAV/UT which does not elicit the full value or utility function, but progressively approximates it from simpler choices made by the decision makers. There are several variants of UTA.

Ref. Jacquet-Lagreze, E. and Siskos, J., (1982) Assessing a set of additive utility functions for multicriteria decision-making, the UTA method. *European Journal of Operational Research,* **10**(2), pp.151-164.

Siskos, Y., Grigoroudis, E. and Matsatsinis, N.F., (2005) UTA methods. In *Multiple Criteria Decision Analysis: State of the Art Surveys* (pp. 297-334). Springer, New York, NY.

Case Study Stavrou, D.I., Siskos, E.Y., Ventikos, N.P. and Psarras, J.E., (2018) Robust Evaluation of Risks in Ship-to-Ship Transfer Operations: Application of the STOCHASTIC UTA Multicriteria Decision Support Method. In *Multi-Criteria Decision Making in Maritime Studies and Logistics* (pp. 175-218). Springer, Cham.

See also Multi-attribute Value and Utility Analysis

OUTRANKING METHODS

MULTI-CRITERIA DECISION AID (MCDAID)

Def. An MCDA approach with several specific algorithms for specific tasks: ELECTRE I, II, III etc. Bernard Roy who led the development provides strong philosophical and methodological foundations in his 1996 book.

Ref. Roy, B. (1990) The outranking approach and the foundations of ELECTRE methods. In *Readings in multiple criteria decision aid* (pp. 155-183). Springer, Berlin, Heidelberg.

Roy, B. (1996) Multi-Criteria Modelling for Decision Aiding. Dordrecht, Kluwer Academic Publishers.

Case Study Haurant, P., Oberti, P. and Muselli, M., (2011) Multicriteria selection aiding related to photovoltaic plants on farming fields on Corsica island: A real case study using the ELECTRE outranking framework. *Energy Policy,* Rogers, S.H., Seager, T.P. and Gardner, K.H., (2004) Combining Expert Judgement and Stakeholder Values with Promethee: A case Study in Contaminated Sediments. In Comparative risk assessment and environmental decision making (pp. 305-322). Springer, Dordrecht. (2), pp.676-688.

PROMETHEE

Def. An approach closely related to MCDAid, but with a greater emphasis on uncertainty issues.

Ref. Brans, J.P. and Mareschal, B., (1990) The PROMETHEE methods for MCDM; the PROMCALC, GAIA and BANKADVISER software. In *Readings in multiple criteria decision aid* (pp. 216-252). Springer, Berlin, Heidelberg.

Brans, J.P. and Mareschal, B., (2005) PROMETHEE methods. In *Multiple criteria decision analysis: state of the art surveys* (pp. 163-186). Springer, New York, NY.

Case Study Rogers, S.H., Seager, T.P. and Gardner, K.H., (2004) Combining Expert Judgement and Stakeholder Values with Promethee: A case Study in Contaminated Sediments. In *Comparative Risk Assessment and Environmental Decision Making* (pp. 305-322). Springer, Dordrecht.

DECISION-MAKING UNDER DEEP UNCERTAINTY (DMDU)

DECISION TABLES

Def. The fundamental elements of a decision rendered into options, states of the world and outcomes. Choices are then made according to various principles, e.g. minimax loss or regret, Hurwicz-α, expected value. Despite their long history in textbooks these methods are seldom applied.

Ref. Luce, R.D, and Raiffa, H. (1989) *Games and Decisions.* New York, Dover Publications Inc.

Milnor, J. (1954) Games against Nature. *In Decision Processes.* R. Thrall, C. Coombs and R. David. New York, John Wiley and Sons: 49-59.

Case Study Pažek, K. and Rozman, Č., (2009) Decision making under conditions of uncertainty in agriculture: a case study of oil crops. *Poljoprivreda,* 15(1), pp.45-50.

ROBUST DECISION-MAKING

Def. A class of tools which provide decision-making support based on the minimisation of downside risk or regret, applicable when there is great uncertainty.

Ref. Groves, D. G., & Bloom, E. (2013) Robust Water-Management Strategies for the California Water Plan Update 2013, Rand Corp.

Weaver, C.P., Lempert, R.J., Brown, C., Hall, J.A., Revell, D. and Sarewitz, D., (2013) Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change,* 4(1), pp.39-60.

Case Study Matrosov, E.S., Woods, A.M. and Harou, J.J., (2013) Robust decision making and info-gap decision theory for water resource system planning. *Journal of Hydrology,* **494**, pp.43-58

ARGUMENT MAPS

Def. A method from epistemology to disaggregate then represent visually the essential elements of a decision or claim. Can be very useful in articulating debate between stakeholders.

Ref. Okada, A. et al. (2008) *Knowledge Cartography.* London, Springer.

Renton, A. and Macintosh, A., (2007) Computer-supported argument maps as a policy memory. *The Information Society,* **23**(2), pp.125-133.

Case Study Van Egmond, S. and Hekkert, M.P., (2012) Argument map for carbon capture and storage. *International Journal of Greenhouse Gas Control,* **11**, pp.S148-S159.

See also Cognitive mapping

COGNITIVE MAPS

Def. A cognitive map is a network which connects different elements showing how the decision makers see them interacting. Can be very powerful in the early stages of developing a quantitative model.

Ref. Ackermann, F., C. Eden and I. Brown (2004). *The Practice of Making Strategy.* London, Sage.

Eden, C., 1988. Cognitive mapping. *European Journal of Operational Research,* 36(1), pp.1-13.

Case Study Eden, C. and Ackermann, F., (2004) Cognitive mapping expert views for policy analysis in the public sector. *European Journal of Operational Research,* **152**(3), pp.615-630.

See also Argument maps, belief nets, influence diagrams, system dynamics

CONFLICT ANALYSIS

Def. An element of strategic analysis, conflict analysis considers the dynamics of relationships between multiple parties.

Ref. Sandole, D.J.D, Byrne, S. Sandole-Staroste, I., & Senehi, J. (editors) (2010) *Handbook of Conflict Analysis and Resolution.* London, Routledge.

Burton, J.W. and Sandole, D.J., (1986) Generic theory: The basis of conflict resolution. *Negotiation Journal,* **2**(4), pp.333-344.

Case Study Delgado, A. and Romero, I., (2016) Environmental conflict analysis using an integrated grey clustering and entropy-weight method: A case study of a mining project in Peru. *Environmental Modelling & Software,* **77**, pp.108-121.

See also Adversarial risk analysis, game theory

SOFT ELICITATION

CYNEFIN

Def. The structure of Cynefin (see Figure 1, p5) can be very useful in soft elicitation, helping decision-makers assess the context of their problem and identify what sort of tools may be useful (see Figure 3, p25).

Ref. French, S. (2013). “Cynefin, Statistics and Decision Analysis.” *Journal of the Operational Research Society* 64(4): 547-561.

Snowden, D. and M. Boone (2007). “A leader’s framework for decision making.” *Harvard Business Review* 85(1): 68-76.

Case Study Van Beurden, E.K., Kia, A.M., Zask, A., Dietrich, U. and Rose, L., (2011) Making sense in a complex landscape: how the Cynefin Framework from Complex Adaptive Systems Theory can inform health promotion practice. *Health Promotion International,* **28**(1), pp.73-83.

DELPHI METHOD

Def. The Delphi method is a structured iterative process, emphasising anonymous consultation, for building a consensus opinion from a group of experts.

Ref. Dalkey, N. & Helmer, O. (1963). “An Experimental Application of the Delphi Method to the use of experts” *Management Science,* 9(3): 458–467.

Rowe, G. and G. Wright (1999). “The Delphi technique as a forecasting tool: issues and analysis.” *International Journal of Forecasting,* **15**: 353-375.

Case Study Kaufmann, P.R., (2016) Integrating factor analysis and the Delphi method in scenario development: A case study of Dalmatia, Croatia. *Applied Geography,* **71**, pp.56-68.

See also Structured expert judgement

HORIZON SCANNING

Def. A systematic and proactive approach to risk identification based on available information.

Ref. UK Government (2014) Futures Toolkit for Policy Makers and Analysts, Cabinet Office.

Könnölä, T., Salo, A., Cagnin, C., Carabias, V. and Vilkkumaa, E., (2012) Facing the future: Scanning, synthesizing and sense-making in horizon scanning. Science and Public Policy, 39(2), pp.222-231.

Case Study Stanley, M.C., Beggs, J.R., Bassett, I.E., Burns, B.R., Dirks, K.N., Jones, D.N., Linklater, W.L., Macinnis-Ng, C., Simcock, R., Souter-Brown, G. and Trowsdale, S.A., (2015) Emerging threats in urban ecosystems: a horizon scanning exercise. *Frontiers in Ecology and the Environment,* **13**(10), pp.553-560.

See also Scenario planning

IMPACT-UNCERTAINTY MAPPING

Def. Qualitatively mapping identified risks according to their impact on an organisation and the likelihood of their occurrence in order to dictate the appropriate organisational response.

Ref. Funtowicz, S. and Ravetz, J. (1993). 'Science for the post-normal age', F*utures,* 31(7): 735-755.

Ramírez, R. and Selin, C., (2014) Plausibility and probability in scenario planning. *Foresight,* **16**(1), pp.54-74.

Case Study Doyle, E.E., Johnston, D.M., Smith, R. and Paton, D., (2018) Communicating model uncertainty for natural hazards: a qualitative systematic thematic review. *International Journal of Disaster Risk Reduction,* 33(2) pp449-476

See also Scenario analysis

SCENARIO ANALYSIS

Def. The discretisation of a range of possible futures into distinct scenarios and analysis of decision-making options in the context of each. Scenario analysis is important in providing backdrops for strategic conversations and also in stress testing of systems.

Ref. Courtney, H. G., Kirkland, J., & Viguerie, S. P. (1997). 'Strategy under Uncertainty', *Harvard Business Review,* November-December issue.

Schoemaker, P. (1995). "Scenario planning: a tool for strategic thinking." *Sloan Management Review* **36**(2): 25-40.

Case Study Spielmann, M., Scholz, R., Tietje, O. and De Haan, P., (2005) Scenario modelling in prospective LCA of transport systems. Application of formative scenario analysis (11 pp). *The International Journal of Life Cycle Assessment,* **10**(5), pp.325-335.

VALUE-FOCUSED THINKING

Def. Beginning, defining a model and managing an analysis by focusing on the values and objectives that you are trying to achieve.

Ref. Keeney, R. L. (1992). *Value-Focused Thinking: a Path to Creative Decision Making,* Harvard University Press.

Case Study Kajanus, M., Kangas, J. and Kurttila, M., (2004) The use of value focused thinking and the A'WOT hybrid method in tourism management. *Tourism management,* **25**(4), pp.499-506.

Merrick, J.R. and Grabowski, M., (2014) Decision performance and safety performance: a value-focused thinking study in the oil industry. *Decision Analysis,* **11**(2), pp.105-116.

See also Multi-Attribute Value and Utility Analysis

ECONOMIC & FINANCIAL APPROACHES

COST-BENEFIT ANALYSIS (CBA)

Def. Cost-benefit analysis is a simple framework, founded heavily in an economic tradition, which pits the benefits of an action or choice against its costs or consequences.

Ref. Mishan, E. J., & Quah, E. (1976). *Cost-Benefit Analysis*, London, Allen & Unwin.

Pearce, D., Atkinson, G. and Mourato, S., (2006) *Cost-Benefit Analysis and the Environment: Recent Developments*. Organisation for Economic Co-operation and Development.

Case Study Neudorf, E.G., Kiguel, D.L., Hamoud, G.A., Porretta, B., Stephenson, W.M., Sparks, R.W., Logan, D.M., Bhavaraju, M.P., Billinton, R. and Garrison, D.L., (1995) Cost-benefit analysis of power system reliability: two utility case studies. *IEEE Transactions on Power Systems*, **10**(3), pp.1667-1675.

GAME THEORY

Def. A class of tools for analysing strategic interactions between multiple agents whose outcomes depend on each other's actions.

Ref. Von Neumann, J., & Morgenstern, O. (1944). *Theory of Games and Economic Behaviour*, Princeton University Press. Princeton, USA.

Colman, A.M., (2016) *Game theory and Experimental Games: The Study of Strategic Interaction*. Elsevier.

Case Study Geckil, I.K. and Anderson, P.L., (2016) *Applied Game Theory and Strategic Behaviour*. Chapman and Hall/CRC.

See also Adversarial Risk Analysis, Conflict Analysis

HURDLE RATE ANALYSIS / RISK ADJUSTED RETURN ON CAPITAL

Def. Adds risk premiums to a company's basic cost of capital in order to determine a threshold internal rate of return for project approval.

Ref. Baer, T., Mehta, A., & Samandari, H. (2011). *The use of economic capital in performance management for banks: a perspective*, McKinsey Working Papers on Risk.

Brigham, E.F., (1975) Hurdle rates for screening capital expenditure proposals. *Financial Management*, pp.17-26.

Case Study de Assis, C.A., Houtman, C., Phillips, R., Bilek, E.M., Rojas, O.J., Pal, L., Peresin, M.S., Jameel, H. and Gonzalez, R., (2017) Conversion economics of forest biomaterials: Risk and financial analysis of CNC manufacturing. *Biofuels, Bioproducts and Biorefining*, **11**(4), pp.682-700.

See also NPV Analysis

LIFE CYCLE ANALYSIS (LCA)

Def. An approach to evaluating systems related to their total lifetime costs from planning and construction through to decommissioning and disposal.

Ref. Ciambrone, D.F., (2018) *Environmental life cycle analysis.* CRC Press.

Hauschild, M.Z., Rosenbaum, R.K. and Olsen, S., (2018) *Life cycle assessment. Theory and Practice.* Springer

Case Study Zakeri, B. and Syri, S., (2015) Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews,* **42**, pp.569-596.

See also NPV analysis

NET PRESENT VALUE (NPV) ANALYSIS

Def. A form of (expected utility) analysis describing the sum of the discounted future net cash flows of a decision option (e.g. a project).

Ref. Gallo, A. (2014). 'A Refresher on Net Present Value', *Harvard Business Review.*

Smit, H.T. and Trigeorgis, L., (2017) Strategic NPV: Real options and strategic games under different information structures. *Strategic Management Journal,* **38**(13), pp.2555-2578.

Case Study Kumar, R., Sharma, A.K. and Tewari, P.C., (2015) Cost analysis of a coal-fired power plant using the NPV method. *Journal of Industrial Engineering International,* **11**(4), pp.495-504.

See also hurdle rate analysis, lifecycle costing analysis, real options

REAL OPTIONS

Def. A form of (Bayesian) analysis which adapts analysis of financial market derivatives to real organisational decision-making, often capturing challenging temporal and informational elements of uncertainty.

Ref. Leslie, K. J., & Michaels, M. P. (1997). 'The Real Power of Real Options', *The McKinsey Quarterly,* 3: 4-22.

Benninga, S. and Tolkowsky, E., (2002) Real options—an introduction and an application to R&D valuation. *The Engineering Economist,* 47(2), pp.151-168.

Case study Torani, K., Rausser, G. and Zilberman, D., (2016) Innovation subsidies versus consumer subsidies: A real options analysis of solar energy. *Energy Policy,* 92, pp.255-269.

See also NPV Analysis

DECISION PROCESS MANAGEMENT

AGENT BASED MODELLING

Def. A type of modelling based on simulating the actions of autonomous agents in their environment, in order to develop an opinion of their effects on the system as a whole. Needs to make assumptions about the beliefs and preferences that drive the agents' behaviours.

Ref. Macal, C.M., (2016) Everything you need to know about agent-based modelling and simulation. *Journal of Simulation,* 10(2), pp.144-156.

Abar, S., Theodoropoulos, G.K., Lemarinier, P. and O'Hare, G.M., (2017) Agent Based Modelling and Simulation tools: A review of the state-of-art software. *Computer Science Review,* **24**, pp.13-33.

Case Study Novosel, T., Perković, L., Ban, M., Keko, H., Pukšec, T., Krajačić, G. and Duić, N., (2015) Agent based modelling and energy planning–Utilization of MATSim for transport energy demand modelling. *Energy,* **92**, pp.466-475.

See also Monte Carlo and Simulation Methods

ENTERPRISE RISK MANAGEMENT (ERM)

Def. ERM describes a class of formal methods and tools for identifying and managing risks and opportunities in organisations, usually businesses. One key tool is a risk register.

Ref. Lam, J. (2003) *Enterprise Risk Management: From Incentives to Controls.* John Wiley & Sons.

Bromiley, P., McShane, M., Nair, A. and Rustambekov, E., (2015) Enterprise risk management: Review, critique, and research directions. *Long Range Planning,* **48**(4), pp.265-276.

Case Study Woods, M., (2012) *Risk management in organizations: An integrated case study approach.* Routledge.

See also Risk Register

RISK REGISTER

Def. A risk management tool which is a repository of all known risks and the actions being taken to mitigate them. Sometimes called an action tracker.

Ref. The Institute of Risk Management (2010) A structured approach to enterprise risk management and the requirements of ISO 31000, AIRMIC; ALARM; IRM.

Raz, T. & Micheal, E. (2001) 'Use and benefit of tools for project risk management', *International Journal of Project Management,* **19**(1): 9-17.

Case Study Ackermann, F., Eden, C., Williams, T. and Howick, S., (2007) Systemic risk assessment: a case study. *Journal of the Operational Research Society,* 58(1), pp.39-51.

See also Enterprise Risk Management

MONTE-CARLO AND SIMULATION METHODS

Def. Methods which explore a (decision model) using algorithms based on stochastic sampling, e.g. of a model's output or real data, when other mathematical processes are unavailable.

Ref. Rubinstein, R.Y. and Kroese, D.P., (2016) *Simulation and the Monte Carlo method* (Vol. 10). John Wiley & Sons.

Sobol, I.M., (2018) *A primer for the Monte Carlo method.* CRC press.

Case Study Baležentis, T. and Streimikiene, D., (2017) Multi-criteria ranking of energy generation scenarios with Monte Carlo simulation. *Applied energy,* 185, pp.862-871.

See also Agent-based modelling, system dynamics

SYSTEM DYNAMICS

Def. System Dynamics is an approach to modelling nonlinear behaviour of complex systems over time. Applicable in social, managerial, economic, ecological and many other contexts, it allows for interdependence, mutual interaction, feedback, and circular causality.

Ref. Abdelkafi, N. and Täuscher, K., (2016) Business models for sustainability from a system dynamics perspective. *Organization & Environment,* **29**(1), pp.74-96.

Forrester, J.W., (1994) System dynamics, systems thinking, and soft OR. *System Dynamics Review,* **10**(2-3), pp.245-256.

Case Study Qu, T., Thürer, M., Wang, J., Wang, Z., Fu, H., Li, C. and Huang, G.Q., (2017) System dynamics analysis for an Internet-of-Things-enabled production logistics system. *International journal of production research,* **55**(9), pp.2622-2649.

See also Systems Modelling

SYSTEMS MODELLING

Def. The interdisciplinary analysis, discretisation, and parameterisation of the mathematical relationships between of interacting agents and their environment, often considering their physical, temporal, and economic interaction.

Ref. Schwarzenbach, J. & Gill, K. (1992). *System Modelling and Control,* 3rd Ed., Butterworth-Heinemann. Oxford, UK.

Harish, V.S.K.V. and Kumar, A., (2016) A review on modeling and simulation of building energy systems. *Renewable and sustainable energy reviews,* 56, pp.1272-1292.

Case Study Rutter, H., Savona, N., Glonti, K., Bibby, J., Cummins, S., Finegood, D.T., Greaves, F., Harper, L., Hawe, P., Moore, L. and Petticrew, M., (2017) The need for a complex systems model of evidence for public health. *The Lancet,* **390**(10112), pp.2602-2604.

See also System Dynamics

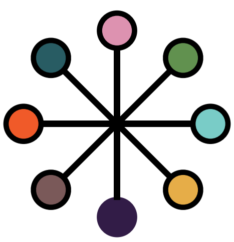
MISCELLANEOUS MODELLING TOOLS

Some tools commonly used in decision modelling are much more general modelling systems and approaches. They provide little more than intuitive ways to structure and program calculations. They embody no specific decision modelling elements. We might, for instance, include spreadsheet modelling here.

8 CATEGORISING DECISION TOOLS
AGAINST CYNEFIN

Figure 3. Since we are primarily concerned with complex decision-making in the face of uncertainty, few of the tools listed relate to the Known Space. That is the domain in which OR and many Analytics approaches dominate. The complete lack of knowledge in the Chaotic Space means that there can be no structured decision tools there. Thus the tools listed here are applicable to the Complex and Knowable Spaces with several spanning the 'boundary' between these.

Miscellaneous modelling tools are not shown. Nor is 'Cynefin' as a tool for exploring uncertainty as it applies in all contexts.



BAYESIAN METHODS

- Adversarial Risk Analysis
- Belief Nets
- Influence Diagrams and Decision Trees
- Multi-attribute Value Theory (MAVT) and Multi-attribute Utility Theory (MAUT)
- Structured Expert Judgement (SEJ)

INTERVAL METHODS

- Dempster-Shafer Theory
- Evidential Reasoning
- Fuzzy Decision Analysis

MCDA METHODS

- Analytical Hierarchy Process (AHP)
- Simple Multi-Attribute Rating Technique (SMART)
- Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)
- Utility Assessment (UTA)

OUTRANKING METHODS

- Multi-Criteria Decision Aid (MCDAid)
- Promethee

DMDU METHODS

- Decision Tables
- Robust Decision-Making

SOFT ELICITATION METHODS

- Argument Maps
- Cognitive Maps
- Conflict Analysis
- *Cynefin*
- Delphi Method
- Horizon Scanning
- Impact-Uncertainty Mapping
- Scenario Analysis
- Value-Focused Thinking

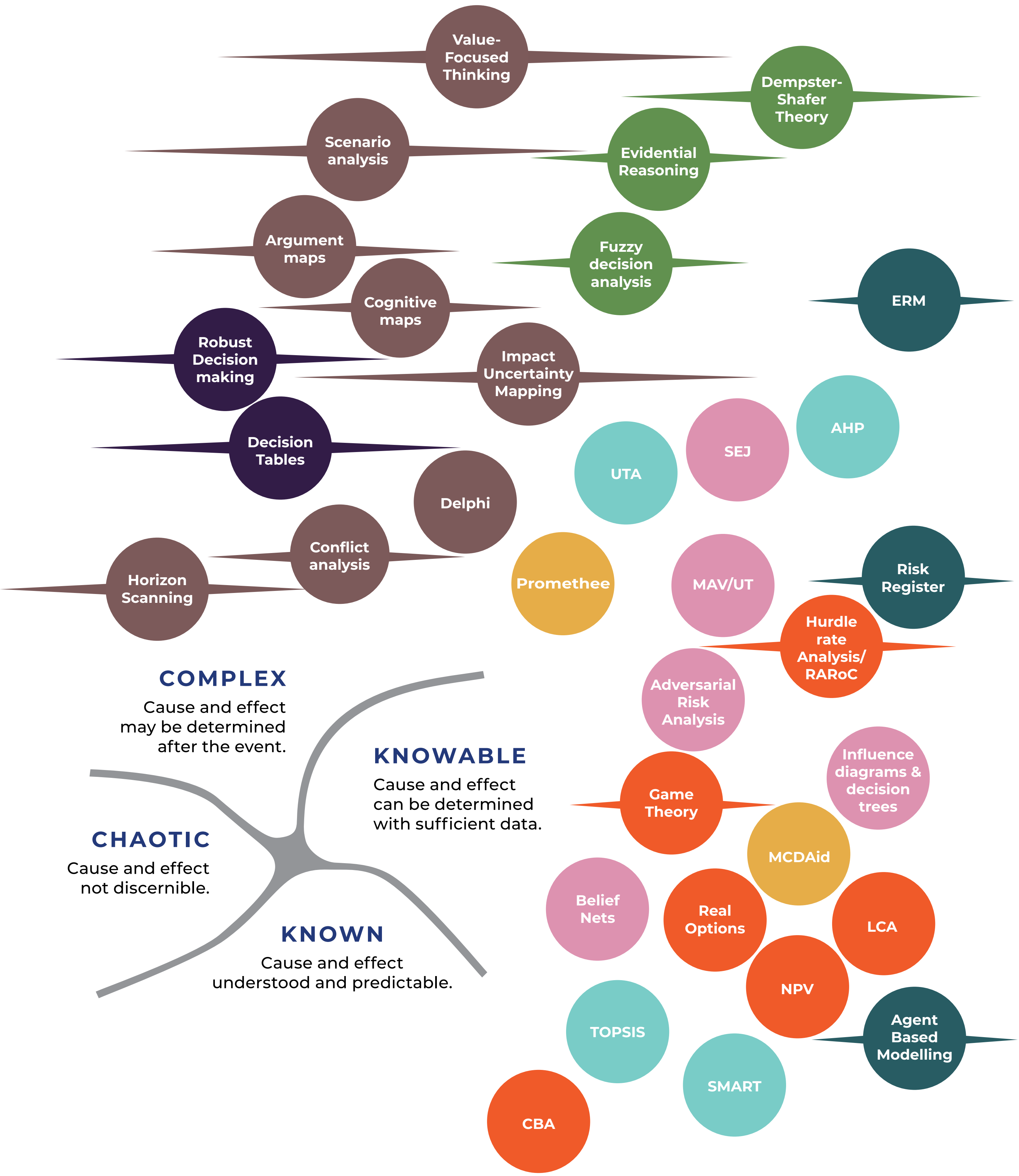
ECONOMIC AND FINANCIAL METHODS

- Cost-Benefit Analysis (CBA)
- Game Theory
- Hurdle Rate Analysis / Risk Adjusted Return on Capital
- Life Cycle Analysis (LCA)
- Net Present Value (NPV) Analysis
- Real Options

DECISION PROCESS MANAGEMENT

- Agent Based Modelling
- Enterprise Risk Management (ERM)
- Risk Register

Position roughly indicates the domain a tool operates in, within the boundaries of Cynefin. Spikes indikate that these tools span boundaries.



9 CATEGORISING DECISION TOOLS
AGAINST THE DECISION-MAKING PROCESS

Figure 4.

The horizontal positioning of a tool indicates where in the decision making process (Figure 2) it fits. As noted earlier, the decision-making process often iterates back and forth between the three stages.

The vertical positioning of the tool indicates whether it tends to provide support for dealing with stochastic, epistemological, and analytical uncertainties; or for ambiguity and value uncertainty; or for both.

Miscellaneous modelling tools are not shown.

BAYESIAN METHODS

- Adversarial Risk Analysis
- Belief Nets
- Influence Diagrams and Decision Trees
- Multi-attribute Value Theory (MAVT) and Multi-attribute Utility Theory (MAUT)
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MCDA METHODS

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- Decision Tables
- Robust Decision-Making

SOFT ELICITATION METHODS

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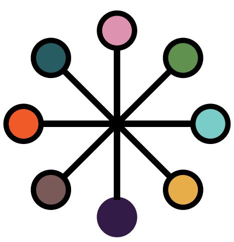
- Conflict Analysis
- *Cynefin*
- Delphi Method
- Horizon Scanning
- Impact-Uncertainty Mapping
- Scenario Analysis
- Value-Focused Thinking

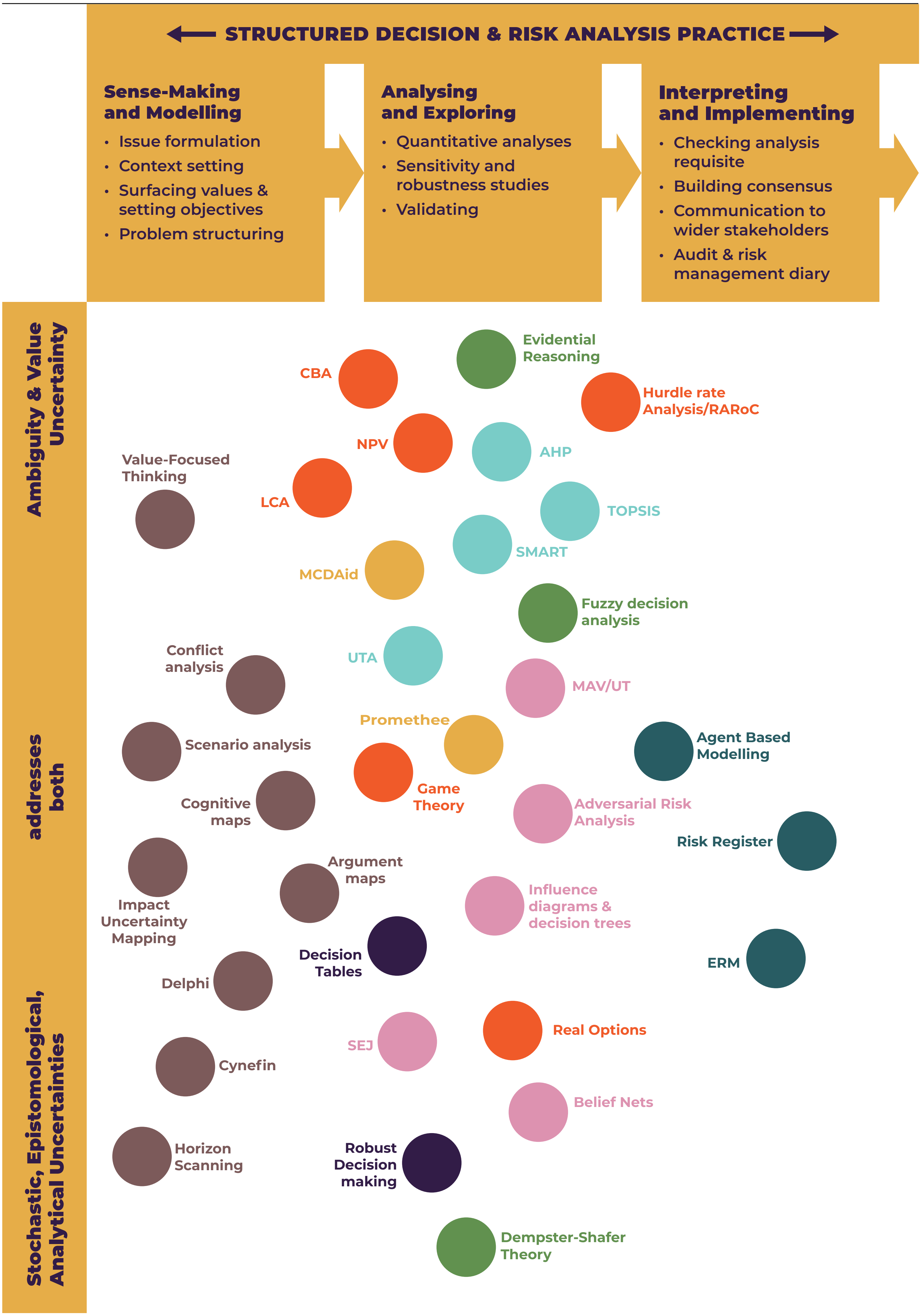
ECONOMIC AND FINANCIAL METHODS

- Cost-Benefit Analysis (CBA)
- Game Theory
- Hurdle Rate Analysis / Risk Adjusted Return on Capital
- Life Cycle Analysis (LCA)
- Net Present Value (NPV) Analysis
- Real Options

DECISION PROCESS MANAGEMENT

- Agent Based Modelling
- Enterprise Risk Management (ERM)
- Risk Register




STRUCTURED DECISION & RISK ANALYSIS PRACTICE
Sense-Making and Modelling
Issue formulation
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Sensitivity and robustness studies
Validating
Interpreting and Implementing
Checking analysis requisite
Building consensus
Communication to wider stakeholders
Audit & risk management diary
Ambiguity & Value Uncertainty
addresses both
Stochastic, Epistomological, Analytical Uncertainties
Evidential Reasoning
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Hurdle rate Analysis/RARoC
NPV
AHP
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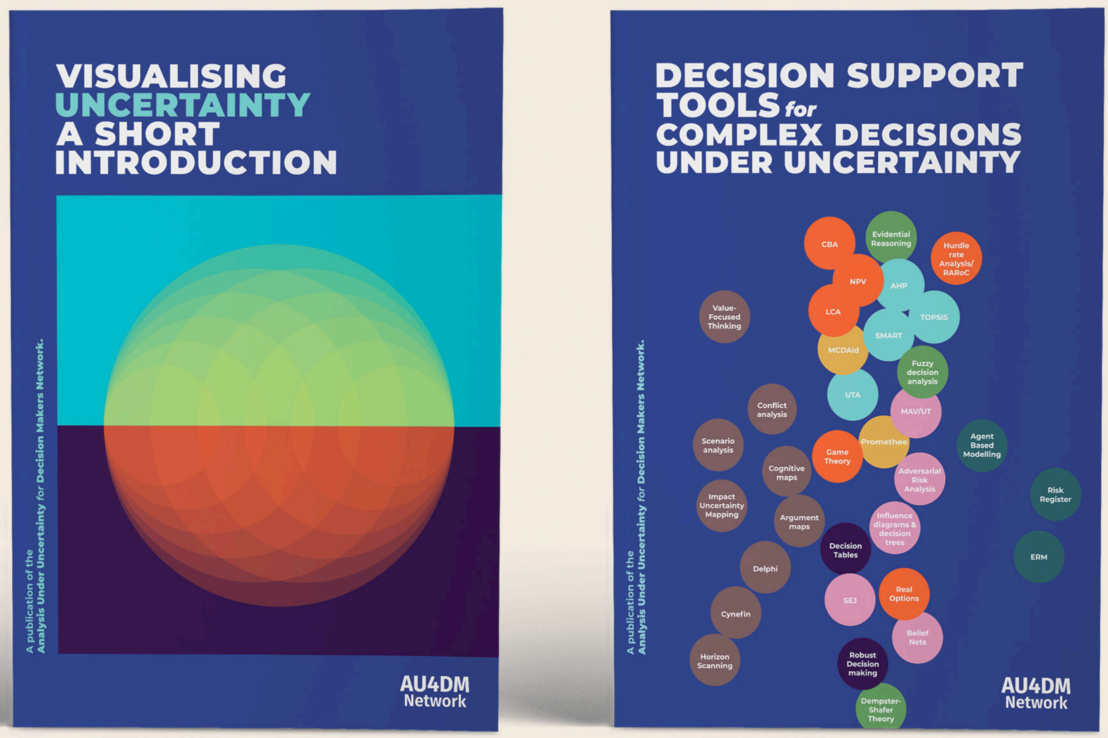

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