Imperial College London

DECISION MAKING UNDER RISK & UNCERTAINTY

Practitioners Round Table - Review and White Paper

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Contributions by Attendees of the *Decision Making under Risk & Uncertainty Workshop*, see Appendix III for list of participating practitioners.

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Grantham Institute
Climate Change and the Environment

Introduction

Decision making is the process of an individual or organisation choosing a course of action. Most individuals make decisions intuitively as a matter of routine. Organisations, however, have the resources to develop and adopt structured processes for decision making to achieve a desired outcome, such as welfare or profit maximisation. These decision making processes are complicated substantially by elements of risk and uncertainty. This white paper attempts to capture how organisations currently understand and address risk and uncertainty in their decision making. By doing so, this paper captures a current state of practise and articulates the need for a research network to support improvements to organisational decision making for the benefit of the economy, environment, and society generally. The word 'organisations' is used in this paper to broadly capture organised human entities with a collective objective, such as governments, public institutions, NGOs, and public and private companies.

Risk and uncertainty arises from conditions of the unknown. Various fields and subdisciplines of decision making manage risk and uncertainty dramatically differently. Is it useful or even possible to capture the widely varying approaches to risk and uncertainty in a single framework? The 21st-century is characterized by the most complex challenges ever faced by human civilization. Environmental systems like weather, water, climate, nitrogen and carbon cycles, biodiversity, and finite resources have unpreceded interaction with the human systems of energy provision, food production, shelter, poverty alleviation, security, finance, commerce, and insurance. Understanding and reconciling how risk and uncertainty is managed in each of these fields will enable the development of a resilient human civilization capable of navigating the complexity of these challenges.

This white paper has been prepared based on knowledge captured during the successful *Grantham Institute Workshop on Decision Making under Risk and Uncertainty*, hosted in February 2016 at Imperial College London[1]. The workshop was developed based on the success of an earlier one-day seminar on game theory hosted May 2015. The workshop attracted over 60 expert attendees from industry, policy making, and academia, coving sectors ranging from defence, security and development, through to water, energy, agriculture, and power. Experts were invited to give pop-up talks and the academic work of risk and uncertainty specialists from the United States, Netherlands, and around the UK was highlighted. All delegates had an opportunity to participate in two one-hour round-table sessions in small groups during which consensus views in the challenges and opportunities with understanding, managing, and communicating risk and uncertainty in organisation decision making were developed.

This white paper has been prepared as a call-to-action and an opinion of research needs based on these consensus views. It reflects the understanding of risk and uncertainty among the practitioners who attended the workshop. References are included in this white paper for illustrative purposes only. Research questions are proposed throughout this document and are aggregated in Annex I.

[1] Workshop presentations and summary report are available at http://tinyurl.com/hmvecwj

Problem Definition

Decision makers must often seek the best course of action despite conditions of the unknown, described by risk and uncertainty. Approaches to risk and uncertainty have developed in all industries and fields, however in certain industries like finance, business, insurance, science, engineering, development, and policy making, risk and uncertainty management has emerged as a critical subdiscipline. Each industry has developed their own definitions of risk and uncertainty, as well as the syntax and tools needed to address their specific needs. Generally, a clear division exists between the definitions of risk and uncertainty in applied sciences and policy and the definitions thereof in business and finance, see Box 1 for two examples.

Box 1: Perceptions of risk and uncertainty

Different industries have developed their own methods for defining and addressing risk and uncertainty. Two examples are given below.

Example 1: Asset management in the finance industry
Asset managers in the finance industry seek to optimise portfolio returns for a given level of risk. With invention of modern portfolio theory and the capital asset pricing model, 'risk' has become interpreted as the volatility of a security relative to a market index of securities, the security's *beta*. According to the theory, the beta of a company's securities can be used to calculate the cost of capital of the company. The cost of capital can then be used in the hurdle rate for company decision makers comparing internal rates of return for prospective projects.

Example 2: Water resource planning
Water utility companies are statutorily obligated to provide a long-term water resource management plan. Uncertainty is understood within the context of the long-term exogenous factors which affect the efficiency of their investment decisions. These companies rely on extensive modelling of uncertainty in weather, climate, technology, consumer behaviour, macroeconomic change, and environmental impacts. Using stochastic analysis techniques, they can define an optimal investment strategy given their modelled range of uncertain exogenous factors.

In applied sciences and policy, uncertainty is generally understood to encompass two dimensions: the fundamental stochastic variability in the state of a system and the limitations of the measurers knowledge (sometimes called *epistemic* and *aleatory* uncertainty respectively). Some authors go further to describe *deep uncertainty*, which is the condition of uncertainty beyond the ability of (or agreement in the development of) statistical models to provide useful insight[2]. In these disciplines, the concept of 'risk' is used in a more operational and normative sense (e.g. the risk of a workplace accident; the risk of cost overruns).

[2] See, e.g., resources from the *Society for Decision Making under Deep Uncertainty*, available at http://www.deepuncertainty.org/

In the fields of business and finance, decision-makers are accustomed to variability in the parameters and results of the decisions they make. Where it is able to be measured and modelled, such variability is referred to as risk. Variability beyond the ability or agreement of modellers to interpret, as in deep uncertainty above, is called uncertainty[3]. One clear research question might be:

- What is the taxonomy of risk and uncertainty and how does it vary across different industries?

Roles of Decision Makers and their Analysts

Types of Organisation

The decision-making process of organisations depends significantly on the type of organisation and its purpose. Many organisations have well-defined purposes and face constraints in the form of limited resources, scope of mandate, or regulatory environment. The decision-maker's goal depends on the organisation type. Policy makers and NGOs may seek to optimise the welfare of a stakeholder group according to their established purpose or mandate. Company decision-making is generally profit-optimising, however the main drivers of company decision making differ if the company is publicly traded or privately held, or operates in highly regulated markets.

Policy makers and NGOs face substantial complication in decision-making from their welfare-related mandates. These mandates are often un-specific (e.g. "to safeguard the natural environment"; "to invest in good people doing good things") which makes it difficult to evaluate the effectiveness of decision-making in service of this mandate. Decision makers must develop distinct criteria from a broad mandate, but often still face challenges optimising resource allocation among multiple criteria, particularly when the trade-offs between them are poorly understood and complicated by risk and uncertainty. Budget allocation decisions may be the simplest reflection of how this complexity is currently addressed: criteria which are currently poorly- or unmet receive greater priority in the decision-maker's interpretation of the organisation's mandate and may thus receive a greater portion of the organisation's total budget.

Among corporate organisations, there is a significant difference in decision-making depending on how regulated the company's operations are. For highly-regulated companies, decision-making is driven substantially by regulatory constraints. Prime examples include regulated monopoly network service companies such as water utilities and electricity transmission and distribution companies.

For companies without substantial regulatory constraints, decision-making is driven by the efficient allocation of capital. For publicly-traded companies, the fiduciary duty of company officers to shareholders demands that decision-making optimise capital allocation to maximise shareholder value. This can lead to excessive short-termism, underinvestment in research and development, and the mismanagement of non-financial risks, like social or environmental risk[4]. Non-public companies

[3] Knight, F. H. (1921). *Risk, Uncertainty, and Profit*, Houghton Mifflin Company. Boston and New York, USA.

[4] 'See Kay, J. (2012) *The Kay Review of UK Equity Markets and Long-Term Decision Making.*

are more free to define their own decision-making objectives, typically aligned with the interests of the company owners, whether individuals, states, etc.

Different organisation types make decisions on distinctly different time horizons, which has a major influence on the action chosen. Often the long-term impacts of uncertainty and risk fall outside the incentive of decision makers to address in the present. This 'tragedy of the horizon',[5] wherein the impacts of a risk occur outside of traditional decision-making cycles, may prevent decision makers from taking preventative or early action which may be more efficient.

Research questions related to how decision making under risk and uncertainty varies by organisation type include:

- What are the interfaces between different organisational types and how can risk and uncertainty management best practises be shared across them? How might different organisation types work together to address critical complications caused by risk and uncertainty? (e.g. how might the insurance industry better accommodate uncertainty in environmental change? How might the finance industry better address uncertain needs in global development?)
- How does the management of risk and uncertainty differ when considering decision making across various time horizons, from short term collapsing, as in emergency services, to very long term, as in infrastructure planning? What complications are developed due to inappropriate time horizons and the tragedy of the horizon and how might they be addressed?

Limits of the Decision-Maker

Decision makers are ultimately humans, with limited attention spans, instincts, experience, personality biases, and appetites for change. Understanding these limits will help enable more effective decision-making. Common cognitive biases include confirmation bias, anchoring, and bias for action. Where decisions are made among groups, social biases also complicate decision making, including group think and group polarization. Identifying these biases as they develop or using processes which avoid them outright will help keep decision making rational and effective.

Decision makers have a limited daily bandwidth to absorb and process information. Information overload can prevent effective decision making. Decision-makers need to be supplied with actionable information by their analysts which is communicated effectively. However this raises questions of with whom ultimate decision-making agency lies. If company board members rarely, if ever, turn down an investment proposal, does that make their analysists and advisors the de-facto decision makers? Analysts might argue that any proposal unfit for execution would not be put forth to the ultimate decision makers, however confirmation and action bias may cause decision-makers to over-rely on the advice of their analysts. As technology and the use of models improves, analysts' advice must ostensibly be improving. Might technical sophistication entirely supplant human decision-makers (perhaps with the exception of their liability as officers)? What is the role of visionary leadership in an era of technocratic decision-making?

[5] See Bank of England (2015). *Breaking the Tragedy of the Horizon – climate change and financial stability*, Speech given by Mark Carney, Governor of the Bank of England.

Better defined roles between analysts and decision-makers may help clarify who is responsible for providing which elements of a successful decision. One option might be that decision-makers attempt to critique the recommendations of their analysts by considering the uncertainties which only their experience and intuition can provide them with. If this is to be the role of company boards in decision making, they must be familiar with the modelling of their analysts and also of their role in decision-making process. There is a need to adapt existing decision-making frameworks slowly, beginning with what decision makers are familiar with and slowly incorporating new tools.

Research questions related to the limits of a human decision maker might be:

- What common biases affect decision makers or decision-maker groups? How can these biases be systematically discovered and countered? How do they differ across nations and cultures?
- What is the role of the decision maker within the larger organisation? What is the role of advisors in the decision making process? What is the role of leadership, experience, and relationships of decision makers in an age of technocratic decision making?

Ownership of Risk and Uncertainty

Internal ownership of risks depends on the organisation. For private businesses, it might be the Board of Directors. For public organisations, it might be the public and politicians. This difference drives the response of decision makers to risk and uncertainty. Organisations with a more strict hierarchy have an easier time identifying who owns risks, however they may have difficulty ensuring free-flowing information. For large organisations, decision making or risk management may be centralised far away from 'on the ground' conditions, however sometimes special accountability structures are created to manage risk – particularly after risks manifest in destructive events. All organisations suffer from agency problems – planning horizons are multiple decades but the career or responsibility of organisational agents may only be a few years.

Risks are not only exogenous to an organisation. Risks may develop internally or may be exacerbated by the actions of organisation members. These risks are usually addressed with policies and codes. There may also exist gaps between an organisation's intended risk management action and the actual outcome thereof. This execution gap can cause the manifestation of risk to surprise the decision makers, who may have thought an appropriate management strategy was executed.

Many organisations which believe they manage risk effectively find themselves unprepared for 'black swans' - unexpected events which deviate far from the normal situation. This belief may be due to industry-wide normalisation of risk-management practises, whether as a cultural norm of practise or even as a standard codified by an industry body. When an entire industry has common risk exposure, and makes decisions the same way, the industry can exhibit pro-cyclic behaviour. This resonant behaviour is unstable, which results in sub-optimal outcomes for all commonly-exposed organisations. In extreme cases, the combination of systemic exposure and pro-cyclic behaviour can destabilise economies, as in the global financial crisis, or industries, as in the consequences of the recent collapse in commodity prices.

Research questions related to the ownership and embedded nature of risk and uncertainty might be:

- How might organisations better identify gaps between the decisions made and their execution? How can ex-post analysis improve the quality of ex-ante projections and decision-making processes?
- How can systemic, embedded, and networked risk exposure be identified and whose role is it to manage these risks?

Managing Risk and Uncertainty

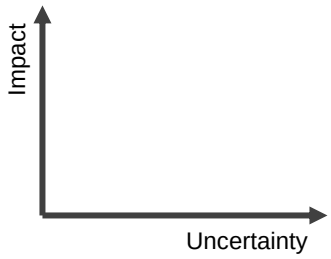

Figure 1 Impact-Uncertainty framework[6]

The saliency of risk to an organisation is the product of the organisation's exposure (i.e. the likelihood of the risk manifesting) and the impact such a manifestation of risk might have on the organisation, see Figure 1. Uncertainty often drives a wedge between risk prevention and risk response measures. Decision makers must overcome a preference for inaction to take preventative measures, which is usually more efficient. Box 2 provides an example of risk management options for flood risk.

There are four options for reducing the saliency of risk to an organisation. Organisations may mitigate risk by reducing the impact the manifestation of the risk would have on the organisation. The risk may also be avoided by reducing exposure to the risk. The risk may be diversified by shifting exposure to other, uncorrelated, risks. The final option for managing risk is to pay a premium to transfer the risk to a third party, e.g. by an insurance contract.

Box 2: Risk management example: flood risk

Mitigate: Install flood protection
Avoid: Relocate assets away from flood-prone areas
Diversify: Relocate some assets to flood-prone areas in other watersheds
Transfer: Purchase flood insurance

Decision-Making Tools

Decision-makers can choose from a wide variety of tools with which to conduct analysis to inform their decision. These tools range from procedural and qualitative to mathematical and quantitative. Different industries have developed decision-support tools to meet their specific needs – seldom are tools available which can meet the needs of more than one industry or even more than one segment of an industry's value chain.

Emerging technology is improving the ability of decision support tools to inform the choices of decision makers. Improvements in sensing and statistical computing are enabling the creation of high-resolution tools for more precise decision-making or more efficient allocation of resources. Not all decision-making is able to be improved by increased computing power and data however, and

[6] See, e.g. Funtowicz, S. & Ravetz, J. (1993). Science for the post-normal age, *Futures*. 31(7): 735-755.

delineating where these advances have disruptive potential for decision making and where they do not has scarce been approached.

A selection of decision support tools is listed in Annex II of this white paper. These tools help identify and substantiate risks and inform decision makers of the trade-offs between their different options. Critically, these tools are limited to supporting decision-making; they are not substitutes for decision making itself, and cannot be due to the unknown nature of uncertainty. Decision makers may also be unprepared to adopt new decision support tools. Rejection of new decision making tools or processes can be harmful as decision makers defer to their instincts or experience for decision-making. Developers of decision support tools must ensure their decision makers are prepared to use them as designed.

Research questions related to the development and use of decision-making tools might be:

- How can current decision making practises be realistically improved in ways that are palatable with current decision makers, their advisors, and stakeholders?
- How might new technologies (e.g. big data analytics, machine learning, pervasive sensing) be used to enhance decision making?

Communicating Risk and Uncertainty

Effective management of risk and uncertainty requires first that risk and uncertainty can be adequately communicated, both internally within the organisation, between multiple organisations coordinating decision making efforts, and externally to the organisation with that organisation's stakeholders. Decision makers and their analysts must often overcome preferences for simplified deterministic analysis, for example reducing investment decisions to a single expected value.

When organisations have a mandate with a broad group of stakeholders, decision making is often subject to delicate relationships of trust (especially with the public, civil society, etc.). Organisations must be able to clearly communicate the uncertain inputs and outcomes of their decision making process in order to maintain acceptance of their organisation's license to operate. Public participation and stakeholder elicitation can serve dual purposes of building confidence in the decision making ability of the organisation while also identifying areas of risk or uncertainty which were previously unknown, particularly qualitative risks like reputational damage or local acceptance.

Non-specific mandates for decision makers can risk that the measure becomes the target. Particularly with welfare-related objectives, proxies and measures may be developed to guide decision making. In these cases, a hazard develops in that decision-makers may focus more on satisfying the proxy or measure, developing myopia of the actual target. Choosing the correct analysis and decision-support tools can be simplified by asking and communicating their recommendations can be simplified by asking appropriate questions of decision makers. By providing decision makers with a mandate-driven guiding question, decision makers and their analysts may choose tools which are fit-for-purpose. Box 3 has examples of effective risk management guiding questions.

Box 3: Asking the correct questions of decision makers

Guiding questions for decision makers should be intuitive and easily communicated, numerically explicit, forward-looking, and should aim for resilience and robustness. Example guiding questions are given below.

Example 1: Electrical Grid Operator

"How can we maintain enough supply of electricity to keep the lights on 99.999% of the time?"

Example 2: Insurance Executive

"How can we remain solvent through a 1-in-200 year financial shock?"

Research questions related to the communication of risk and uncertainty might be:

- How might decision makers communicate measures of risk and uncertainty management which accurately reflect their objective? How might they avoid the hazard of managing to their measure rather than their target?
- How can important qualitative measurements or projections (e.g. of social impacts, reputational impacts) be better integrated into organisational decision making?
- How might risk and uncertainty be better communicated – both to decision makers and their wider stakeholders and the public? How can risk and uncertainty be better communicated between organisations of different types (e.g. with better visual aids, cross-sector vocabularies, and widely applicable case studies)? How can transparency and provenance be integrated into decision making processes?

Conclusion

Understanding how different organisations define and manage risk and uncertainty is critical to developing solutions to complex inter-organisational problems. Defining the roles and limits of decision makers within their organisations will be critical for developing organisations which can adopt advanced decision-making processes. Addressing embedded cultural norms, avoiding myopic perspectives of risk and uncertainty, and identifying procyclic behaviour will ensure a new culture of effective risk and uncertainty management is able to develop. Communicating risk and uncertainty effectively between organisations and their stakeholders is critical to its effective management. This century comes with no shortage of challenges complicated by risk and uncertainty; building organisations which are capable of working together to respond to these challenges will help ensure prosperity for all.

Annex I: Questions for Research

Interdisciplinary understandings of risk and uncertainty are in their infancy. Questions for research are shown in Table 1.

Table 1: Interdisciplinary risk and uncertainty research questions

##	Research Question
Q1	What is the taxonomy of risk and uncertainty measurement and management across different organisation types?
Q2	What are the interfaces between different organisational types and how can risk and uncertainty management best practises be shared across them? How might different organisation types work together to address critical complications caused by risk and uncertainty? (e.g. how might the insurance industry better accommodate uncertainty in environmental change? How might the finance industry better address uncertain needs in global development?)
Q3	How does the management of risk and uncertainty differ when considering decision making across various time horizons, from short term collapsing, as in emergency services, to very long term, as in infrastructure planning? What complications are developed due to inappropriate time horizons and the tragedy of the horizon and how might they be addressed?
Q4	What common biases affect decision makers or decision-maker groups? How can these biases be systematically discovered and countered? How do they differ across nations and cultures?
Q5	What is the role of the decision maker within the larger organisation? What is the role of advisors in the decision making process? What is the role of leadership, experience, and relationships of decision makers in an age of technocratic decision making?
Q6	How might organisations better identify gaps between the decisions made and their execution? How can ex-post analysis improve the quality of ex-ante projections and decision-making processes?
Q7	How can systemic, embedded, and networked risk exposure be identified and whose role is it to manage these risks?
Q8	How can current decision making practises be realistically improved in ways that are palatable with current decision makers, their advisors, and stakeholders?
Q9	How might new technologies (e.g. big data analytics, machine learning, pervasive sensing) be used to enhance decision making?
Q10	How might decision makers develop measures of risk and uncertainty management which accurately reflect their objective? How might they avoid the hazard of managing to their measure rather than their target?
Q11	How can important qualitative measurements or projections (e.g. of social impacts, reputational impacts) be better integrated into organisational decision making?
Q12	How might risk and uncertainty be better communicated – both to decision makers and their wider stakeholders and the public? How can risk and uncertainty be better communicated between organisations of different types (e.g. with better visual aids, cross-sector vocabularies, and widely applicable case studies)? How can transparency and provenance be integrated into decision making processes?

Annex II: List of Tools and Practises

This annex lists a number of tools and practises generated by workshop attendees. References have been added as examples only, to direct users to further reading.

Action Tracker

Def. A tool for tracking identified risks and the actions which need to be taken to respond to them.

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

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.

Ref. Axelrod, R. (1997) *The Complexity of Cooperation: Agent-based models of competition and collaboration*, Princeton University Press. Princeton, USA.

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*, Routledge. London, UK.

Cost-Benefit Analysis

Def. Cost-benefit analysis is a simple framework which pits the benefits of an action or choice against its costs or consequences.

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

Delphi Method

Def. The Delphi method is a structured communication method for eliciting information and opinions from 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.

Dempster-Shafer Theory

Def. Dempster-Shafer theory is a generalised form of belief theory, which is capable of probabilistically handing how new information can influence beliefs in a stochastic model.

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

Enterprise Risk Management

Def. ERM describes a class of formal methods and tools for identifying and managing risks and opportunities in organisations, usually businesses.

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

Expected Utility Analysis

Def. Describes an expected benefit as a single value given a set of uncertain inputs.

Ref. Stigler, G. J. (1950). 'Development of Utility Theory II', *The Journal of Political Economy*, 58(5): 373–396.

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.

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.

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.

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. & Ravetz, J. (1993). 'Science for the post-normal age', *Futures*, 31(7): 735-755.

Linear Programming and Mathematical Optimisation

Def. A suite of computational tools for finding the optimal solution of a (linear) mathematical model.

Ref. Bertsimas, D. & Tsitsiklis, J. N. (1997). *Introduction to Linear Optimisation*, Athena Scientific. Belmont, USA.

Monitoring and Measuring Analytics

Def. Statistical and sensory processes for benchmarking and monitoring performance. Early identification of deviations allows the appropriate responses to changing or manifesting risks.

Ref. Biggeri, L. (2004). 'Measuring for Decision Making', *OECD World Forum on Key Indicators*, 10-13 November 2004, Palermo. OECD.

Multi-criteria decision making (MCDM)

Def. A class of tools for decision making when an organisation has multiple objectives they seek to optimise.

Ref. Köksalan, M., Wallenius, J., & Zoints, S. (2011). *Multi-Criteria Decision Making: From Early History to the 21st Century*, World Scientific Publishing Co.. New York, USA and London, UK.

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*.

Numerical Methods and Monte-Carlo Sampling

Def. Computational algorithms based on stochastic sampling, e.g. of a model's output or real data, when other mathematical processes are unavailable.

Ref. Mackay, D.J.C. (1998). 'Introduction to Monte Carlo Methods', in Learning in Graphical Models, *Nato ASI Series*, 89: 175-204.

Qualitative analysis

Def. Subjective non-numeric analysis of a topic or subject to capture or compare important attributes for which no quantitative analysis is available.

Ref. Patton, M. Q. (1990). *Qualitative evaluation and research methods*, Sage Publications. Thousand Oaks, USA.

Real Options Theory

Def. A form of 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.

Risk Hedging

Def. Decision making which reduces the negative impact of a risk manifesting by securing a commiserate positive impact should the same risk manifest.

Ref. Chance, D. M. & Brooks, R. (2014) *An Introduction to Derivatives and Risk Management, 10th Ed*., Cengage Learning. Boston, USA.

Risk Register

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

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

Risk Transfer

Def. Contracting for a third party to absorb the impact of a manifestation of a risk, typically via an insurance contract.

Ref. Dionne, G. (editor) (2013). *Handbook of Insurance, 2nd Ed.,* Springer-Verlag. New York, USA.

Robust Decision Making

Def. A class of tools which provide decision making support based on the minimisation of downside risk or regret.

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

Scenario Development and Analysis

Def. The discretisation of a range of possible futures into distinct scenarios and analysis of decision making options in the context of each.

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

Sensitivity Analysis

Def. Statistical analysis which examines the change in a desired output relative to a change in input parameter.

Ref. Saltelli, A., Chan, K., & Scott, E.M. (editors) (2000). *Sensitivity Analysis*, John Wiley & Sons. New York, USA.

Stakeholder Elicitation and Engagement

Def. An outreach and engagement process for discover stakeholder knowledge and interests in a decision making problem.

Ref. Kodikara, P.N., Perera, B.J.C. & Kularathna, M.D.U.P (2010). 'Stakeholder preference elicitation and modelling in multi-criteria decision analysis – A case study on urban water supply', *European Journal of Operational Research*, 206(1): 209-220.

Stochastic Modelling

Def. Systems modelling which involves probabilistic inputs, processes, and outputs.

Ref. Taylor, H. M. & Howard, S. (1998). *An introduction to stochastic modelling, 3rd Ed*., Academic Press. San Diego, USA.

Subject Matter Expertise

Def. The organisational procurement of expertise (either internal or external to the organisation) in the risk management of an asset or processes.

Ref. Larmore, S. (2011). 'Subject Matter Expert: Working Towards Ensuring the Value in a Project Organisation', a thesis prepared for a Master's of Science in Organisational Dynamics, University of Pennsylvania.

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.

Annex III: Workshop Participants

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