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Considering Risk and Resilience in Decision-Making

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Abstract

This paper examines the concepts of decision-making, risk analysis, uncertainty and resilience analysis. The relation between risk, vulnerability, and resilience is analyzed. The paper describes how complexity, uncertainty, and ambiguity are the most critical factors in the definition of the approach and criteria for decision-making. Uncertainty in its various forms is what limits our ability to offer definitive answers to questions about the outcomes of alternatives in a decision-making process. It is shown that, although resilience-informed decision-making would seem fundamentally different from risk-informed decision-making, this is not the case as resilience-analysis can be easily incorporated within existing analytic-deliberative decision-making frameworks.

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1. Introduction

Decision-making is the process of choosing among alternatives. The nature and context of decisions can vary and there can be a variety of criteria to be considered in making a choice. The alternatives can involve a large number and different levels of uncertainties about the factors that influence the ultimate outcomes. For high-consequence decisions with potential outcomes that can have a large impact on valued things, such as human life, property, wealth, and the environment, the decision-making process should involve consideration of uncertainties about the outcomes.

This paper presents an examination of the high-stakes decision-making process with consideration of the uncertainties associated with the alternatives. The next section presents a brief overview of the concept of decision-making. This is followed by a review of risk-informed decision-making, in which potential negative outcomes are considered in the selection of an alternative. In situations of high consequence and uncertainty, the robustness of the alternatives in the sense of insensitivity to uncertainties may be an advantageous consideration to increase confidence in the expected outcome of the selected alternative. A simple framework for resilience-informed decision-making is proposed to complement a risk-informed decision-making process. A summary and final remarks conclude this article.

2. Decision-Making

A decision is a resolution on an issue or a problem of interest being considered. The process of making a decision involves three elements: values, alternatives, and facts (Buede, 2009). **Values** are the criteria used to assess the utility of the outcome. Depending on the context, values can be objective or subjective, and quantitative or qualitative. The values capture the needs, objectives, and preferences of the stakeholders, which are the people and organizations that have an interest and can influence or be influenced by a decision. The **alternatives** may be given or can be the result of a creative process to generate potential solutions to the problem of interest. The **facts** are everything known about the alternatives and the context or environment in which the alternatives will be deployed or applied. Facts are the relevant data, information, and knowledge used in the process of assessing the alternatives against the values in order to make the decision. The decision makers use available facts, history, experience, and judgment to select an alternative.

NASA's Systems Engineering Handbook (NASA, 2007) describes a generic decision-making process. The essential steps are as follows:

1. Define the criteria for evaluating alternative solutions
2. Identify alternative solutions to address decision issues
3. Select evaluation methods and tools
4. Evaluate alternative solutions with the established criteria and selected methods
5. Select recommended solutions from the alternatives based on the evaluation criteria
6. Report analysis results with recommendations, impacts, and corrective actions

In general, decision-making is an iterative analytic-deliberative process consisting of a technical sub-process to analyze the problem and the alternatives, and a deliberation sub-process to assess the alternatives and inform the analysis. The analysis and deliberation processes are iterated with information flowing between them until a final decision is made (Ersdal & Aven, 2008) (Zio & Pedroni, 2012).

An important consideration in the definition of a decision-making process is the cost and time required to implement the process. Generally, a formal decision-making process is used only for decisions involving:

- High stakes (i.e., the outcome can have a significant impact on cost, safety, etc.),
- Complexity (i.e., outcomes are difficult to understand),
- Uncertainty (i.e., inadequate knowledge to assess and rank alternatives with high confidence in the outcome),
- Multiple criteria (i.e., formal analysis methods may be needed to resolve conflicts among evaluation criteria), and
- Diversity of stakeholders (i.e., stakeholders may have different and conflicting values and preferences) (NASA, 2007) (Klinke & Renn, 2002).

A formal decision-making process must be justified by a cost-benefit argument that considers the potential impact of the outcome and the resources and time needed to implement the process.

Hester et al. (2012) have proposed a system for classifying stakeholders and determining an appropriate level of engagement in making decisions about a system. The classification attributes include:

- Power (i.e., ability to influence other stakeholders),
- Legitimacy (i.e., actions are proper or desirable within some socially constructed system of norms, beliefs, or definitions), and
- Urgency (i.e., degree to which stakeholder's views require immediate action).

Additionally, Hester et al. consider the level of support of particular stakeholders for system-related decisions, with the categories of supportive, mixed, non-supportive, and marginal. Based on the patterns of degrees of these attributes, Hester et al. propose a set of strategies for engagement and involvement of the stakeholders in the decision-making process. These strategies include: involve, collaborate, defend, monitor, and no action.

A number of techniques are available for individual and group decision-making. Techniques for individual decision-making include:

- Prioritization (i.e., rank by order of importance),
- Satisficing (i.e., heuristic of selecting the first alternative that meets minimum requirements),
- Opportunity cost (i.e., the benefit received from selecting a different alternative),
- Bureaucratic (i.e., structured and objective criteria-based), and

- Elimination (i.e., process of comparison and elimination of alternatives that do not meet selected criteria and continuing until only one alternative remains).

Group decision-making techniques include:

- Consensus (i.e., majority decision with minority support to go along),
- Voting (e.g., majority or plurality), and
- Delphi method (Helmer, 1967).

A major concern and source of difficulty in high-consequence decision-making is the presence of uncertainty about the alternatives. The causes of uncertainty include:

- Lack of information or knowledge,
- Abundance of information or knowledge,
- Conflicting nature of pieces of information,
- Measurement errors, linguistic ambiguity, and
- Subjectivity of analysis opinions (Zio & Pedroni, 2012).

Uncertainties can also be classified as:

- Knowledge uncertainty (i.e., only sparse statistics or random data are available),
- Modeling uncertainty (i.e., incomplete or inaccurate models), and
- Limited predictability or unpredictability (i.e., outcome is highly sensitive to initial conditions) (Aven T. , 2006).

Fundamentally, decision-making uncertainties are either aleatory (i.e., due to inherently random processes) or epistemic (i.e., due to lack of knowledge about properties and conditions of phenomena that determine the behavior of a system) (Zio & Pedroni, 2012). Epistemic uncertainty can be reduced by acquiring knowledge, but aleatory uncertainty is irreducible. Uncertainty is a fundamental limitation on the effectiveness of a decision-making process.

3. Risk Analysis

Risk has been defined as "the potential for an unwanted outcome resulting from an incident, event, or occurrence as determined by its likelihood and the associated consequences" (DHS, 2010). However, there are multiple perspectives on the concept of risk (Aven T. , 2006). One definition of risk is the *combination* of probabilities and consequences, where the consequences are assessed in terms of valued things such as health, the environment, and safety. Another definition of risk is the expected value of consequences given by the *product* of probabilities and consequences. Risk has also been defined as a combination of the elements of events, consequences, probabilities, and uncertainties. In the most general approach, these elements are kept and handled separate, as there is no agreement on a reducing mathematical formulation that is universally suitable for all decision situations (Aven T. , 2010). Other definitions of risk include the "effect of uncertainty on objectives" and "a situation or event where something of human value (including humans themselves) has been put at stake and where outcome is uncertain" (Aven T. , 2010).

There are seven domains where risk is a major consideration:

- Environmental risk (i.e., related to events such as floods and pollution),
- Lifestyle risk (i.e., related to food, drugs, driving, and so on),
- Medical risk (i.e., related to medical treatments, surgery, etc.),
- Interpersonal risk (i.e., social relationships, parenting, and others),
- Economic risk (i.e., such as investment, employment decisions and events),
- Criminal risk (i.e., being a victim of illegal activity), and
- Technical risk (i.e., accidental side effects of technological innovations) (Johansen, 2010).

In all domains, the focus is on likelihood and severity of future consequences of present decisions and actions.

One view on the purpose of risk analysis is "to understand a risk in order to do something about it" (Johansen, 2010). However, at a more basic level, risk reduction is not the primary goal of a risk assessment. Risk analysis serves to provide input to a particular decision-making process with a wider range of additional considerations (Johansen, 2010). Thus, risk assessment is a tool to generate information that contributes to reducing the uncertainty of decision makers about the outcome of decision alternatives.

Risk analysis can be based on deterministic and probabilistic analysis methods (Kirchsteiger, 1999). **Deterministic risk analysis** is based on worst-case assumptions that bound the uncertainties on likelihood and severity of consequences. This effectively simplifies the analysis and provides reasonable assurance that the risk level is acceptable. A problem with this approach is that the definition of worst-case conditions is subjective and potentially arbitrary, which can lead to consideration of scenarios which are possible but highly unlikely. Deterministic risk analysis is a conservative approach that offers only broad (and not deep) insight into the likelihood of possible outcomes. **Probabilistic risk analysis** (PRA) is intended to be more objective, detailed, and quantitative and offer deeper insight into the relative likelihood of outcomes and the implications of uncertainty. NASA has published a comprehensive guide on PRAs (NASA, 2011). PRA is centered on the quantification of risk metrics, which are probabilistic performance measures that appear in decision models. Examples of risk metrics are the probabilities of fuel tank explosion and of system failure. Such metrics and the techniques used in their calculations can offer insight into the relative importance of various sources of uncertainty and serve as a reference in optimal resource allocation decisions. In general, the output of a risk analysis consists of undesirable risk-significant scenarios, the consequences of those scenarios, the probabilities, and the uncertainty or confidence in the results of the analysis (NASA, 2011).

Various processes have been proposed for risk analysis (NASA, 2010) (NASA, 2011) (Johansen, 2010)

(Biringer, Vugrin, & Warren, 2013). The basic steps are:

1. Define the system,

2. Identify the alternatives,

3. Identify the hazards (i.e., what can go wrong),

4. Estimate the likelihood and consequences for each hazard, and

5. Combine the results into a single comprehensive risk picture.

A wide range of analysis tools and techniques are available, including fault tree analysis; failure mode and effects analysis; and modeling and simulation. The risk analysis results are used in risk assessments where the goal is to assess the confidence in the analysis results and decide whether the level of risk is acceptable, tolerable (i.e., operationally manageable), or unacceptable.

The effectiveness of risk assessments is complicated by three major factors that limit the accuracy of the results (Ben-Haim, 2012). These include our evolving understanding of the world and its uncertainties, the inherent random nature of physical phenomena, and the fact that learning from experience involves untestable assumptions in rational processes of inductive reasoning about the physical world. Considerations of ontological uncertainties (i.e., what exists and its nature) and epistemological uncertainties (i.e., acquisition and thoroughness of knowledge about what exists) complicate the assessment of risk as it is clear that truly objective and accurate assessment of risk is not possible, except for the simplest of situations. Situations involving complexity, uncertainty, and ambiguity necessarily require subjective judgments and considerations of stakeholder values and preferences to arrive at a decision.

4. Risk-Informed Decision-Making

There are two basic approaches for using risk information in decision-making: risk-based and risk-informed (Johansen, 2010). **Risk-based decision-making** considers only risk assessment results to make decisions. This approach may be adequate for simple systems when the stakeholders are aligned in their values and preferences. Safety-critical decision-making processes may follow this approach. On the other hand, **risk-informed decision-making** (RIDM) considers risk along with other sources of information, such as cost-benefit analyses and laws and regulations, to compare and deliberate on the preferred alternative. The basic steps of RIDM are:

1. Selection of alternatives,

2. Risk analysis for each alternative, and

3. Alternative selection (Zio & Pedroni, 2012) (NASA, 2010).

Note that RIDM is an iterative analytic and deliberative process in which information can flow both ways between analysis and deliberation to ensure that alternative generation, risk analysis, and deliberation for alternative selection are adequate and as detailed and complete as needed to ensure an explicit and defensible decision. RIDM is the preferred approach when there is a multitude of stakeholder values and preferences (i.e., ambiguity), and there is a need to find the best alternative that satisfies multiple objective and subjective criteria. Both deterministic and probabilistic analysis results may be use in RIDM. Large groups of stakeholders from diverse segments of society may participate in the generation of alternatives and the process of deliberation (NRC, 1996). In such situations, risks may be traded against other attributes in order to ensure selection of the best overall alternative (NASA, 2007) (Amendolla, 2001).

The research literature on risk analysis and risk-informed decision-making is extensive. The principal issues are the disambiguation and definition of concepts, dealing with uncertainty, strategies for dealing with risk, and communicating risk to the decision makers[1]. Risk and RIDM are very complex topics and there is not a single solution that fits all possible situations. Instead, each situation requires consideration of the specific circumstances and framing the problems and approach to ensure adequate coverage of relevant factors. Complexity, uncertainty, and ambiguity are the major categories of consideration in choosing a RIDM approach (Amendolla, 2001).

Ersdal and Aven (2008) have identified five common decision principles used in RIDM:

- Cost-benefit analysis (i.e., choose the alternative that maximizes the total benefit taking into account costs, possible losses due to negative outcomes, and any expected income or benefit);

- Risk acceptance criteria (i.e., the risk is compared to a threshold level of acceptability);

- Cautionary and precautionary principle (i.e., seek alternatives that are robust or insensitive to uncertainties in the likelihood of severe outcomes by avoiding those outcomes and reducing their impact should the undesired outcomes occur);

- As Low As Reasonably Practicable (ALARP) principle (i.e., all available risk reduction (likelihood, severity, and uncertainty) should be implemented unless gross disproportion between cost and benefit can be demonstrated); and

- Multi-attribute analysis (i.e., where multiple criteria, including risk-related ethical factors, must be considered in deliberations to identify a suitable and balanced alternative).

Multi-attribute decision-making is the most general situation. The decision principle applied depends on ethical, safety, and economic considerations, as well as the risk posture of the stakeholders (i.e., the acceptable level of risk for a particular potential level of reward).

Decisions with high uncertainty and potentially high negative consequences require special consideration. In these situations, it may be the judgment of experts and scientists that the likelihood of strongly negative consequences is not insignificant, but the effectiveness of a risk analysis is limited by a high level of epistemic and aleatory uncertainty. Ethical considerations may then be strong determinants of the proper course of action (Aven T. , 2006). In some situations, the major uncertainty is in the likelihood of the hazards. This is the case in infrastructure risk assessments where the threats can be random or deliberate with the range of threats including natural events, accidents, and malevolent actions (Biringer, Vugrin, & Warren, 2013). In this case, it may be advantageous to avoid direct estimation of the likelihood of hazards and instead consider assessments of the overall threat environment (i.e., possibilities, capabilities, motive, etc.) (Haimes, 2009). Application of the cautionary and precautionary principle then leads to consideration of alternatives aimed at avoiding hazards and mitigating the effects of hazards that

[1] The Bibliography lists many relevant references on these issues.

may occur (Johansen, 2010). In effect, the desirable alternative is one that offers a high degree of robustness (i.e., insensitivity), and thus, assurance against uncertainties.

5. From Risk to Resilience

The concept of risk is not adequate if the likelihood of hazards is highly uncertain. In that case, the emphasis should be on the analysis of the consequences of potential hazards. For this, risk is decomposed into hazards and vulnerability (Ciurean, Schroter, & Glade, 2013):

Risk = Hazard x Vulnerability

A hazard is a "dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (Ciurean, Schroter, & Glade, 2013). In addition, Ciurean et al. (2013) state that "Within the risk management framework, vulnerability pertains to consequence analysis" and "defines the potential for loss to the elements at risk caused by the occurrence of a hazard." Furthermore, Aven (2011) has referred to vulnerability as the antonym of robustness. According to Johansen (2010): "Regardless of the improbability of an event, unfortunate outcomes may still occur. Reducing vulnerability on the other hand, will always attenuate risk through reduced consequence severity. Especially important in this are cases of great epistemic uncertainty." Johansen describes vulnerability as composed of three elements:

- Exposure (i.e., effectiveness of protection against initiation of disruption due to hazards),
- Sensitivity (i.e., degradation in performance due to propagation of hazard effects), and
- Resilience (i.e., ability to bounce back after a disturbance).

Robust mitigation of hazard effects requires a balanced allocation of resources to minimize vulnerability in a cost-effective manner. All of these factors would be considered in a comprehensive analytic-deliberative decision-making process for high consequence situation.

Francis and Bekera (2014) proposed a resilience concept that encompasses three capacities:

- Absorptive (i.e., ability to absorb and contain the effects of hazards),
- Adaptive (i.e., the ability to internally adapt to compensate for exceedance of absorptive capacity), and
- Recovery/restorative (i.e., ability to return to normal or improved level of performance).

Many other definitions of resilience have been proposed in the literature. Biringer et al. (2013) list 23 different definitions proposed by different authors. Haimes (2009) defined resilience as "the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within acceptable time and composite costs and risks." Aven (2011) has also examined some existing definitions of vulnerability and resilience in the literature and proposed that vulnerability is assessed with respect to a fixed set of hazard events, while resilience is assessed relative to any set of hazards. From this perspective, vulnerability is a special case of resilience. Biringer et al.'s decomposition seems better aligned with the common sense of the notion of resilience as the ability to cope with change, including resisting degradation and recovering in a timely manner. From this perspective, Biringer et al.'s concept of protection aligns with Johansen's concept of exposure, and Biringer et al.'s resilience would include the concepts of sensitivity and resilience in the sense described by Johansen (2010). That is:

Vulnerability = Protection x Resilience

and

Risk = Hazard x Protection x Resilience.

6. Resilience-Informed Decision-Making

Risk analysis considers three questions: What can go wrong? How likely is it? What are the associated consequences? (NASA, 2011). A risk analysis should also consider the uncertainty. Thus, the risk analysis elements are:

- Scenarios,
- Likelihood,
- Consequences, and
- Uncertainty.

From this perspective, resilience analysis should be an explicit and integral element of the analysis of consequences, and the results of these analyses should be included in the considerations of risk-informed decision-making. Alternatively, a dedicated resilience analysis would consider a wide range of potential hazards to assess the capability of the system to absorb, adapt, and recover. Resilience analysis would be similar to robustness and sensitivity analyses and have the goal of determining the range of possible effects under conditions of high uncertainty.

A resilience-informed decision-making process would not be significantly different from a risk-informed decision-making process. Both approaches acknowledge that decision-making for high consequence situations requires consideration of technical as well as social factors such as the values and preferences of the stakeholders, especially to define the decision criteria and the acceptable level of uncertainty in the outcome of decisions.

Figure 1 illustrates a generic informed decision-making framework that includes various types of analyses to generate critical information for consideration in the process of stakeholder deliberation. This framework is based on the one presented by Johansen (2010), and it is similar to the Risk-Informed Decision-Framework used by NASA and the US Nuclear Regulatory Commission (USNRC) (Zio & Pedroni, 2012) (NASA, 2010) (NASA, 2011) (NASA, 2007) (Johansen, 2010).

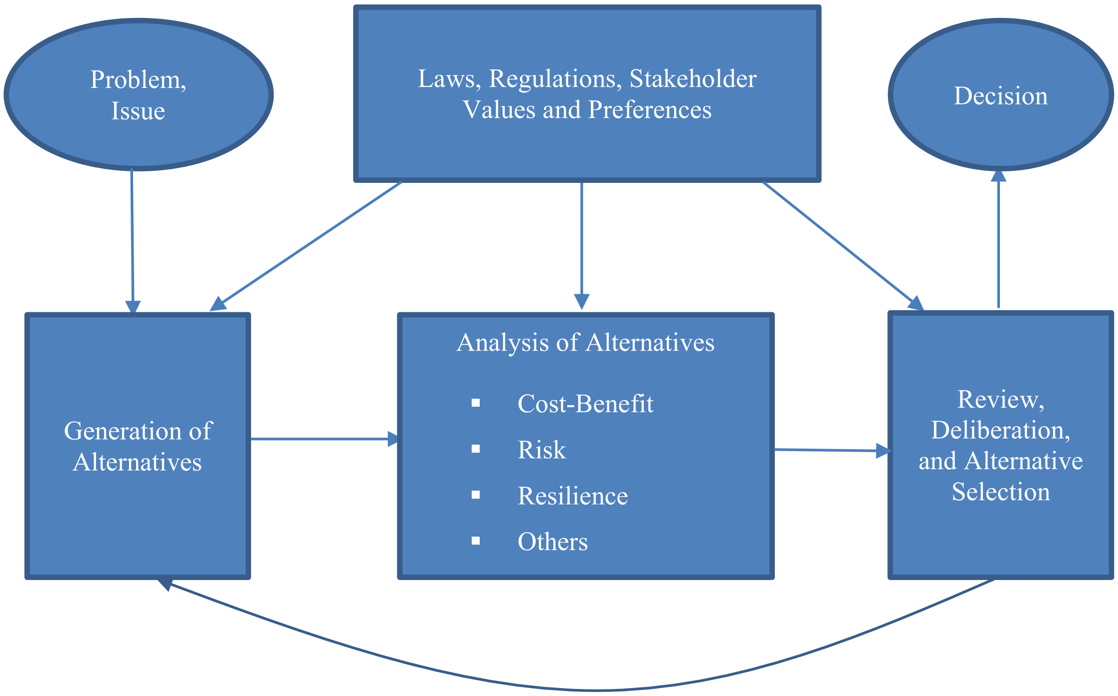

Figure 1: General Analytic-Deliberative Decision-Making Framework (adapted from (Johansen, 2010))

7. Final Remarks

This paper has presented an examination of the concepts of decision-making, risk analysis, uncertainty, and resilience analysis. The relation between risk, vulnerability, and resilience was analyzed. In addition, a resilience-informed decision-making approach that builds on existing informed decision-making frameworks was proposed.

This paper provides insight into the breadth and depth of available published work produced by risk researchers worldwide. Additionally, the paper shows that, although resilience-informed decision-making would seem fundamentally different from risk-based decision-making, this is not the case as resilience-analysis can be easily incorporated within existing analytic-deliberative decision-making frameworks. The paper also describes how complexity, uncertainty, and ambiguity are the most critical factors in the definition of an approach and criteria for decision-making. The paper also offers insight into the approaches for structuring, analyzing, and managing uncertainty. Ultimately, uncertainty in its various forms is what limits our ability to offer definitive answers to questions about the outcomes of alternatives in a decision-making process.

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14. ABSTRACT

This paper examines the concepts of decision-making, risk analysis, uncertainty and resilience analysis. The relation between risk, vulnerability, and resilience is analyzed. The paper describes how complexity, uncertainty, and ambiguity are the most critical factors in the definition of the approach and criteria for decision-making. Uncertainty in its various forms is what limits our ability to offer definitive answers to questions about the outcomes of alternatives in a decision-making process. It is shown that, although resilience-informed decision-making would seem fundamentally different from risk-informed decision-making, this is not the case as resilience-analysis can be easily incorporated within existing analytic-deliberative decision-making frameworks.

15. SUBJECT TERMS

Complexity; Consequence; Likelihood; Resilience; Risk; Uncertainty

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