CRANFIELD UNIVERSITY

ENGINEERING DOCTORATE PROGRAMME:
DEVELOPMENT OF A RISK BASED DECISION SUPPORT SYSTEM FRAMEWORK FOR STRUCTURAL ASSET MANAGEMENT

WORKING PAPER

Subject: A REVIEW OF DECISION ANALYSIS METHODS FOR APPLICATION TO RISK BASED MANAGEMENT OF STRUCTURAL ASSETS

Author: **Caroline M Roberts**
Reliability Engineering and Risk Management Group, SIMS

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1 CONTENTS

2 Introduction

For centuries, many of the world's great philosophers have debated the hypothesis that human behaviour is, as a rule, rational. Depending on one's interpretation of the term "rational" this has been found to be more or less true. If rationality is determined by the ability to remain unaffected by one's emotions, or to understand one's personal motivations and base decisions on them, then yes, with effort, man can be rational. However, if rationality is determined by the ability to consider all options equally and select the optimal one, then man struggles with this unaided.

Many decisions that have to be made are complex in nature. Decisions may involve multiple, conflicting objectives, where a better outcome in one objective results in a worse outcome in another. Decisions may involve some degree of uncertainty, where an uncertain outcome relies on the occurrence of an uncertain future event. Some decisions may be sequential in nature, i.e. one decision cannot be made until the results of a previous decision are known. Decisions may also involve multiple stakeholders, where different people or groups of people, with different levels of authority and influence, may have different objectives and preferences in a certain decision.

It is in the face of such complexity that man struggles to be rational and decision theory becomes useful. Psychological research has shown that the brain finds it very difficult to simultaneously consider more than a limited amount of information at any one time [1]. Therefore decision analysis decomposes the decision problem into a set of smaller and easier to handle problems. After each smaller problem has been dealt with separately, decision theory provides a method to integrate the results so that a course of action can be selected [2]. An important fact is that decision theory will not solve a decision problem, nor is it intended to. Its purpose is to produce insight into the problem, to help decision makers learn about their own and other's values and objectives concerning the decision problem and to promote creativity to help decision makers make better, more rational, decisions.

Decision analysis requires the decision-maker to be clear and explicit about his or her judgements. This makes it possible to trace back through the analysis to discover why a particular course of action was preferred. This "audit trail" means that it is possible to use decision analysis to produce a defensible rationale for choosing a particular option.

This overview of decision analysis has been produced as an initial review of the appropriate methods that could be used to support the risk based decisions that are required in the process of management of structural assets. These could include pipelines, bridges, power plants buildings and other capital equipment used for profit making purposes within in industry. All of these decisions aim to minimise the probability and consequences of failure as perceived by the stakeholders. This overview will briefly describe the history of the development of decision analysis, identify the key principles of decision analysis and describe the decision analysis process and the types of methods available.

Decision analysis is, however, a very broad subject. The full scope of decision analysis encompasses a wide range of diverse subjects and theories such as soft systems methodologies, the theory of constraints, neural networks and many more. It is not possible to tackle such a wide range of subjects within a working paper. Therefore, this paper is concerned with just a subset of decisions where there is a finite number of alternative courses of action being considered and a finite number of alternative outcomes. This form of decision analysis is sometimes referred to as “Classical Decision Theory”.

The limitations and strengths of each process within classical decision theory will be discussed in the context of application to decision problems associated with the management of structural assets.

3 Characteristics of Rational Decision Making

The aim of decision theory is to help the decision-maker to make rational decisions. But what is a rational decision? Lee [3] lists four characteristics of a rational decision:

1. A rational decision is one from a specified set of possible decisions. This means that the decision-maker must have identified all possible decisions before a rational choice can be made of which is globally best. If all possible alternatives are not identified, then the best decision will only be the best of the available decisions and could therefore be sub-optimal.

2. A rational decision depends on the decision principle employed by the decision-maker. The decision principle is the rule or criterion for specifying which of the set of possible decisions is rational.

3. The rational decision for any particular decision situation may differ between decision-makers. This is because subjective probabilities differ between people and the value of particular consequences (utility) differs between people.

4. A rational decision is dependent on the relevant information available to the decision-maker. It is judged irrational to ignore available information that is relevant to a particular decision. But there may be excessive information available that would take considerable time to assimilate. Alternatively, there may be information available, but at a cost. The decision-maker has to determine how much time, effort and money to expend to obtain the information required to make a “rational” decision.

4 Introduction to the Generic Engineering Decision Problem

Decision analysis has, in the past, predominantly been used in very limited fields such as finance, commerce, government and medicine. Very little use has been made of decision analysis methods in the field of engineering and it is specifically this area that will be considered in this review. Engineering by its very definition is concerned with detailed analysis of machines and structures, on the results of which decisions are to be made. These decisions can be concerned with product design, feasibility, production, marketing, sales or maintenance. Often the analysis is performed with extreme care and accuracy. However, the decisions are made largely based on subjective judgement and intuition, taking into account just one or two dominating criteria, combined with conservative assumptions on the uncertain variables. The potential of decision analysis to improve engineering decision-making is significant and could result in the more successful application of engineering solutions.

In nearly every industry, many difficult and complex decisions are made concerning the industry's assets right throughout the asset's life cycle. In this case an asset is defined as an investment which supports the business, either produced by the business for revenue (e.g. for a car manufacturer this would be a car) or used by the business to support the acquisition of revenue (for a roadside rescue service this would also be a car). We can define the stages of the life cycle as concept design and/or selection, detailed design/specification, manufacture/procurement, installation, pre-operational testing, operational maintenance and repair, life extension and finally, decommissioning. For different industries these classifications can mean quite different activities but the significant point is that all these stages involve decision making of some form. In some situations these decisions could be quite simplistic but in other situations they will be highly complex, involving a large number of alternatives, uncertainty and vagueness in the quantification of base data, conflicting objectives on which the decisions are to be based and different stakeholder viewpoints competing for attention. In the offshore oil and gas industry this situation is magnified by the high risks to safety and the environment and the high levels of investment (Capital and operational) involved.

At each stage of the life cycle, the type of decision, the number of alternatives available, the uncertainty in the information available and the number of people influencing the decision, all vary. In later life decisions, there are a limited number of decision alternatives (such as whether to repair a structure or replace it), the consequences of the decision are not significant enough to interest more than a small localised group of stakeholders, the costs involved are less than the initial capital investment and uncertainties can be more effectively modelled due to the amount of historical data obtained.

In contrast, decisions that are made early on in the life cycle involve significant investments, a vast range of alternatives, extreme uncertainties and lack of information. Also these decisions tend to be of high profile, with significant input from senior management. A wide range of stakeholders will also try to influence the decision. It is therefore, considered, that such decisions would have the potential to benefit even more significantly from the support of decision analysis than those discussed in previous work. In addition, a well-defined and evaluated decision at the conceptual stage could prevent the need for a difficult decision later on in the life of the installation.

4.1 *Typical Decision Scenarios*

The typical decision scenarios faced at each stage of a structure's life cycle have been investigated and the multiple criteria on which these decisions should be made, identified. Examples of typical decision scenarios were analysed at each stage along with key influential factors. These are summarised below.

4.1.1 Field Identification and Feasibility Assessment

Before any investment is made in a structural asset, the need or opportunity for such an investment has to be identified/justified. For example in bridge industry, the need or opportunity to transport traffic across an obstruction (road, river, railway) has to be justified before ways of bridging the obstruction the can be investigated. An example in the oil and gas industry is where the need or opportunity to produce oil and/or gas from a new field development has to be justified before ways of developing the field can be investigated. Decisions at this stage are taken at a high level in an organisation's structure and are based on limited data, subjective judgements and predictions of capacity, turnover, whole life cost and profit.

4.1.2 Initial Development

Having decided to cross a river, for example, the development strategy for providing a suitable crossing has to be defined. This initially involves the selection of different development concepts or ideas that could benefit the bridge design. These could be diverse and very creative at this stage. For example, one option to transport people across the river could be the provision of a chain ferry at one end of the scale or a six lane river crossing at the other end of the scale. At this stage a huge amount of uncertainty is involved. For example, the full capacity of the bridge would still be largely unknown, as would environmental factors, with little guidance from historical data. For the oil and gas example, the field development strategy would have to be defined. One option to transport products from the field could be a subsea pipeline to tie in to an existing trunk line. The uncertainties involved in either of these examples significantly affect decisions made at this stage.

4.1.3 Conceptual Design

Conceptual design is the definition of a design based on the selected concepts. Concepts are integrated into a set of design proposals allowing selection of the most promising conceptual design. For example, if the above concept to provide the river crossing via a six lane bridge was proposed, the issues that would have to be considered at the conceptual design stage would include:

- Where the bridge would start and finish
- What elevation it would be built at
- What materials and construction techniques would be used, and so on.

For the oil and gas example, different issues would have to be considered in the conceptual design of a method to transport oil and gas from the field. These issues would include:

- How and where the pipeline should tie in to the trunk line
- What capacity it should have.

The purpose of the conceptual design stage is to check the feasibility and the cost effectiveness of the selected concepts before any significant investment is made. These decisions are also influenced significantly by the very high uncertainties in the different decision attributes.

4.1.4 Detailed Design

By the detailed design stage, the investment is almost definitely approved and the size of the investment is well estimated. The purpose of this stage is to design for safety and whole life cost. This is when dimensions and materials are selected and assessed for safety and durability. Protective measures are identified and additional data is gathered if necessary. These decisions are governed less by uncertainty (although some uncertainties inevitably remain, such as magnitudes of loads), and more by engineering predictions of safety, based on analysis and testing.

4.1.5 Manufacture/Procurement

At this stage, the investment has been approved, as has the proposed design. There are few decisions to make here, but they are still significant and can be heavily influenced by different stakeholders (e.g. preference for certain contractors/suppliers).

4.1.6 Installation

The decisions concerning the installation and construction schedule are very important. They govern the timeliness of completion, the accuracy of construction, and hence the need for post-installation remedial works. These decisions influence the commission date, the whole life cost and profit of the project. These decisions are dominated by uncertainties in the manufacture completion/ delivery of components and environmental conditions.

4.1.7 Pre-operation testing and inspection

The most serious of incidents suffered by bridges occur when the bridge is load tested prior to commissioning. Similarly more pipelines fail in the North Sea during the hydrotest than at any other time. Therefore it is imperative that the best decisions possible are made at this time to ensure minimum risk of structural failure. This is the time when maximum investment has been made, but before the return on investment has begun. These decisions are also affected by uncertainties in environmental conditions and the accuracy with which operational and test conditions can be monitored and controlled.

4.1.8 Inspection, Maintenance and Repair Strategy

All industries rely heavily on well maintained structural assets to ensure safety of personnel and the environment, efficient operation and maximum service and profit. A rational method for deciding maintenance strategies to minimise down-time and costs is required. These decisions are affected by uncertainties in inspection results and deterioration prediction models.

4.1.9 Requalification/Life Extension

When a bridge is requalified its design is reassessed under changed design conditions. This may be initiated by changes in operational parameters such as dead load or traffic volume, excessive deterioration, unexpected damage, such as cracks, weld defects or corrosion, or due to a need to extend the bridge's life. Similarly, when a pipeline is requalified its design conditions will also have changed due to changes in pressure, temperature or corrosivity of the transported product, excessive deterioration, unexpected damage, such as dents, weld defects or corrosion, or due to a need to extend the pipeline's life. These decisions are affected by uncertainties in historical and inspection data, and uncertainties/vagueness in the future design requirements.

4.1.10 Decommissioning

When a bridge is no longer required for operations, it has to be decommissioned. The main objective of bridge decommissioning is to take it out of operation to a safe state. Similarly when a pipeline is no longer required for operations, it also has to be taken out of operation to a safe and clean state. Uncertainties in the current condition, environmental conditions and future requirements have to be accounted for.

4.2 The Generic Decision Problem

In recent years, particularly in the field of structural engineering, there has been less demand for the design of new structures but increased demand for better management of existing structures. The decisions that have to be made in relation to the management of existing structures to ensure safety, maximum service life, minimum cost and many other important factors, can become quite complex. The aim of this work is to apply the established methods of decision analysis to the complex area of engineering, particularly, the management of engineering structures.

Before a decision scenario can be modelled, all factors affecting the decision problem must be understood. For that reason, a generic decision scenario has been defined in the form of an entity diagram as shown in Figure 1. The entity diagram describes all major entities that are involved in risk based decision making, for structural asset management, as blocks and the relationships between them as lines linking the blocks, [4].

To help describe the generic decision problem and its solution an example decision problem has been adopted to illustrate each of the important points. The example decision has been taken from the field of bridge management and considers the need to restrict, maintain or repair an under-strength bridge. The example will be defined in more detail through the course of this discussion.

The starting place for defining the entity model was the construction of the following research statement:

The aim of the research is to "*develop a decision support system for managing the risk of a structural asset, to minimise the probability and consequences of "failure" as perceived by the stakeholders*".

All of the key entities and relationships were then mapped on to the entity model as shown in Figure 1. The description of this model is as follows.

4.2.1 The decision

The focal points of the entity model are the decision and the structural asset, as these are the purpose for the model. But it must be clear in the minds of all parties what the structural asset is that is being considered, what the decision is that is to be made, how it can be made, what constraints the different decision makers have placed on the decision. A major part of defining the decision is identifying the alternatives that are available, being certain that all viable possibilities are considered, how the best one can be selected, whether the different decision makers have a different view of which is best.

In this example, the decision is to identify whether a bridge that has failed assessment should be repaired, strengthened, or left as it is for another year. There are a number of different repair and strengthening alternatives available and new techniques may still be identified as the problem develops. The constraints that would be placed on the decision are predominantly budgetary and safety related.

4.2.2 The decision making group

The Decision making group consists of the Asset manager, the asset management group and other stakeholders. All of these people have an interest and an influence on the decision, but to different extents. One of the first stages in preparing for the decision analysis is to determine who is in the decision making group and to what extent each person can and wants to, influence the decision.

The stakeholders are described as people who have an interest in the availability and/or safety of the structural asset. In the case of our decision example, they would include users of the bridge (private, commercial and industrial), environmental pressure groups (campaigning for pedestrianisation, etc.) or government officials (MPs from local constituencies, etc.). It is necessary to address who the different stakeholders are, how they can be identified, what different roles they play in the decision process and how these roles can be accounted for in the decision support system.

The asset management group would be the committee responsible for allocating annual budgets for each asset manager. In this example this would be a group within the local government or the Highways Agency. It is necessary to identify who the members of this group are, what the group dynamics are, who holds the power in the group, and how decisions are made and agreed within the group.

The asset manager is the person responsible for the day-to-day operation of the asset. His job would be to define maintenance and repair schedules and bid for the required funding. In this example, this would be the county or borough bridge engineer. He could also be a member of the asset management group. It is necessary to identify who the asset manager is and what power he has over the decision process.

4.2.3 The perceptions of the decision makers

Each of the different decision-makers will have different perceptions of the issues involved in the decision problem. They will have different perceptions of which are the important issues and how severe the different risks are. These perceptions will have to be identified and accounted for in the decision process. In this example some stakeholders may consider that the safety of people using the bridge is of utmost importance. For others, though, keeping the bridge open for use by buses and/or heavy goods vehicles may be more important. The different decision-makers are likely to have different preferences over the criteria on which the decision should be made. They are also likely to have preferences over the types of consequences that could happen and the probabilities of those consequences (they could be risk prone or risk averse). These preferences need to be identified, measured and modelled.

4.2.4. Assessment of the risks

One of the objectives of the decision being made is to minimise the risk of failure of the structure. There are a number of definitions of risk currently in use by different groups of risk assessors. These were summarised in a report by the Royal Society [5] as:

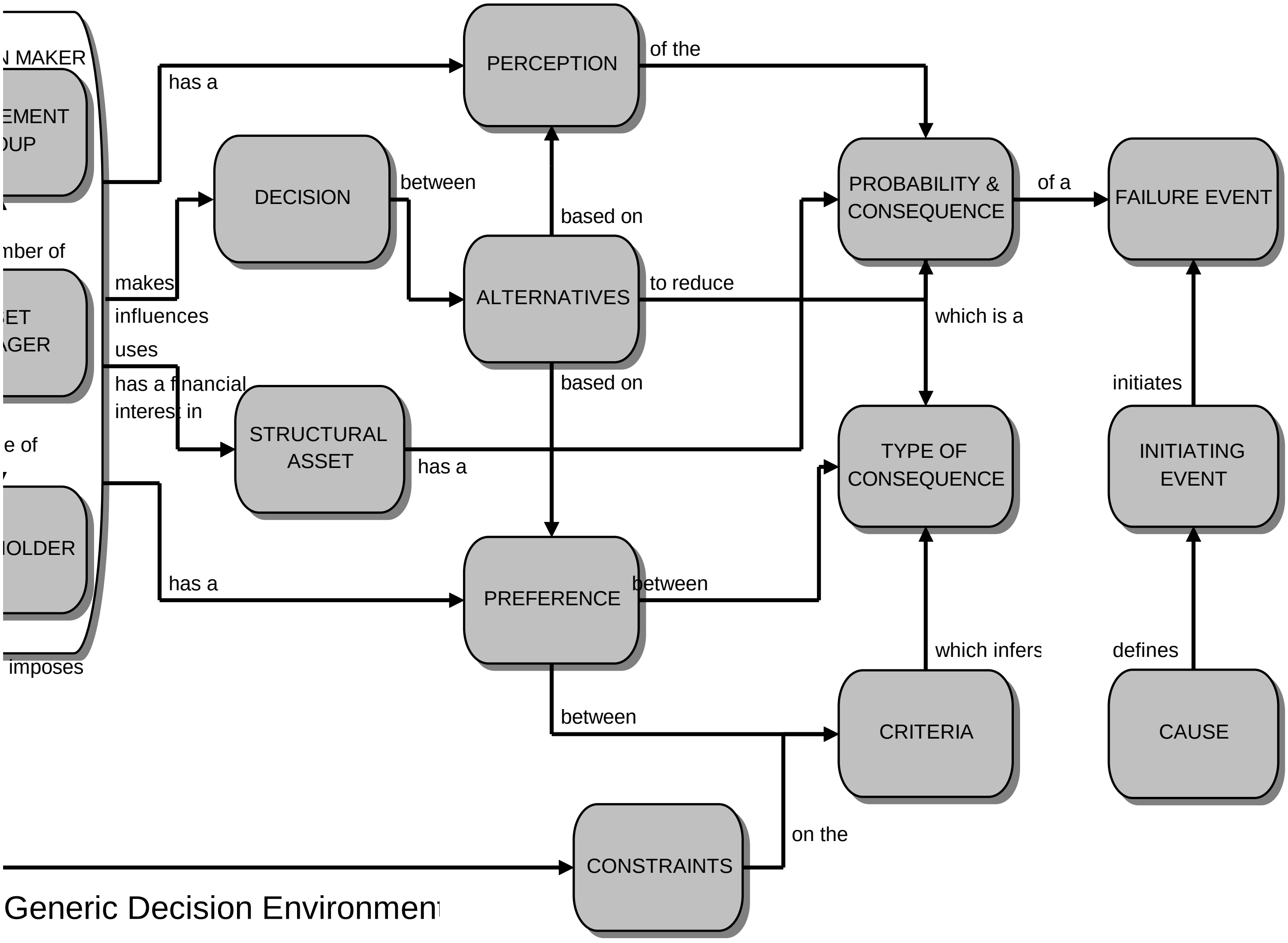
1. Probability of undesired consequences.
2. Seriousness of (maximum) possible undesired consequences.
3. Multi-attribute weighted sum of components of possible undesired consequences.
4. Probability * seriousness of undesired consequences (“expected loss”).
5. Probability weighted sum of all possible undesired consequences (“average expected loss”).
6. Fitted function through graph of points relating probability to extent of undesired consequences.
7. Semivariance of possible undesired consequences about their average.
8. Variance of all possible consequences about mean expected consequences.
9. Weighted combination of various parameters of the probability distribution of all possible consequences.
10. Weight of possible undesired consequences (“loss”) relative to comparable possible desired consequences (“gain”).

Each of these definitions seems logical in its own right, yet each are different. Some are more complex than others. It is expected that complexities of consequence uncertainty and multiple attributes will be introduced later in the decision analysis, therefore, in line with standard engineering risk assessment practice, the definition that has been adopted in this work is definition number 4:

$$\text{Risk} = \text{Probability of failure} * \text{Consequence of failure}$$

The risks considered are as a result of the different possible failure events. It is necessary for the decision process to clarify what failure events are being considered and to be sure that they are fully defined. All decision-makers need to agree that this is “failure”. Associated with each failure event are one or more probabilities and consequences. The probability of the failure event will need to be calculated with an understanding of how accurate the value is and what the value means. The consequences of the failure events need to be identified, how likely they are and how they can be quantified. In the example problem, the consequences of bridge failure could be traffic disruption, disruption to local businesses and shops, damage to the environment, cost of repair, compensation, death and injury.

The purpose of this work is threefold. Firstly it can be used as a basis for structuring a decision support system, as it provides a model for all of the information that is required. Secondly it provides a generic template for discussing all decision problem case studies. Finally it provides a checklist for all areas that need to be considered/researched for the decision support system to be complete.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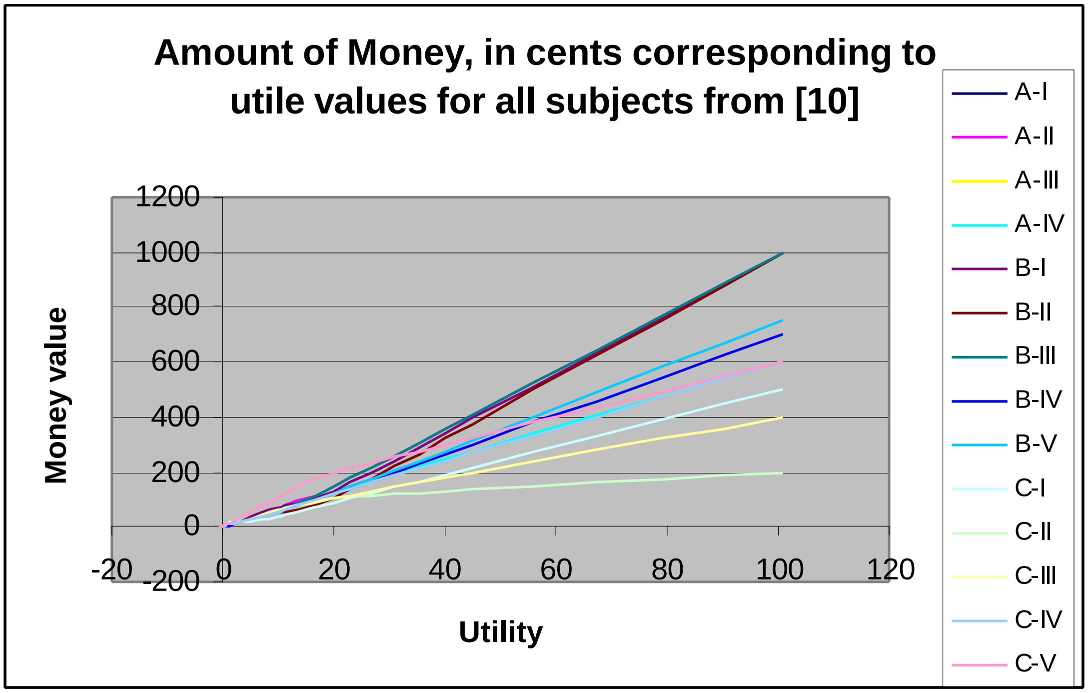
5 A Review of Risk Based Decision Making

The first official seeds of decision theory seem to have been sown early this century in two different fields. In the field of economics, Alfred Marshall [6] described “economic man” as basing his decisions not on habit or custom, but on deliberate and knowledgeable reasoning about the possible results of his decision. His final choice is the course of action that can be expected to bring him maximum gain. In the field of mathematics, Ramsey [7] was the first to express an operational theory of action based on both judgmental probability and utility adopting the subjective or decision-theoretic point of view.

Von Neumann and Morgernstern [8] then developed the modern probabilistic theory of utility in 1947. Utility theory had been first thought of in the seventeenth and eighteenth centuries but was dropped in the mid nineteenth century as being an unmeasurable science. They revitalised utility theory and pointed the way to scientific methods to provide measures for conflicting criteria, by being the first to devise a set of axioms for preferences between gambles. Mosteller and Nogee [9] set out to test the descriptive adequacy of Von Neumann - Morgenstern theory by measuring the utility for small amounts of money for real people. The utility functions they found were very typical and an example is shown in Figure 1. A criticism, was raised of their technique, that people do not, as they assumed, use objective probabilities for decision-making. Davidson, Suppes and Siegel [10] followed up Ramsey’s [7] methods for subjective probability and utility that was free of this criticism. The utility functions, for money, which they found, were also typical and are shown in Figure 2.

Figure 1 Typical utility curve based on experiments by Mosteller and Nogee



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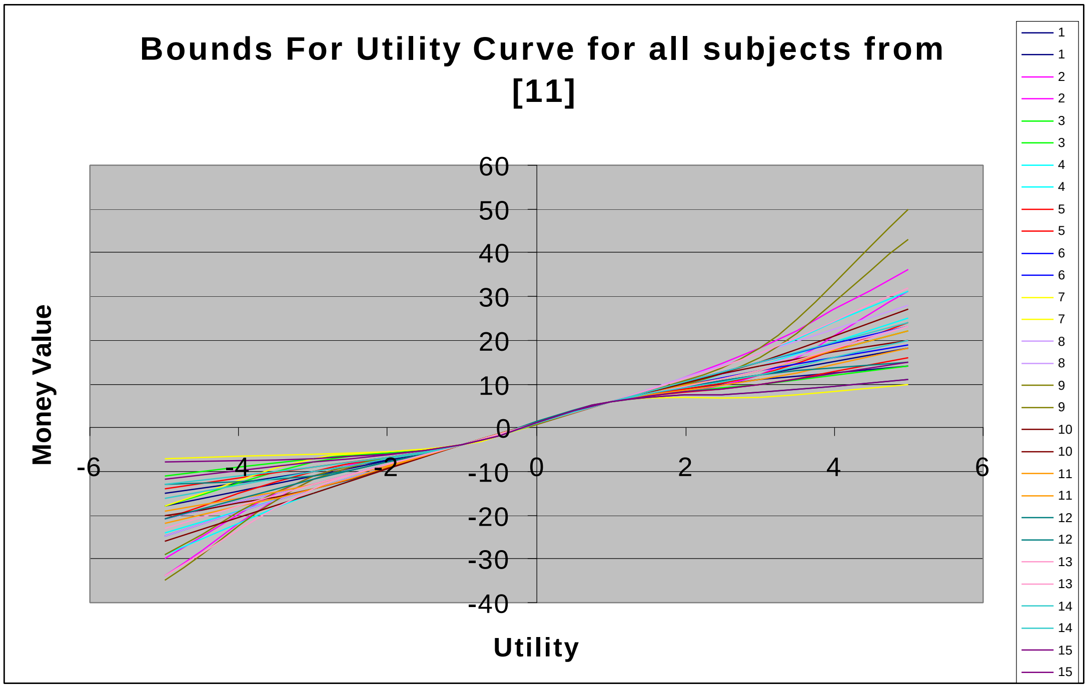

Figure 2 **Typical utility curve based on experiments by Davidson, Suppes and Siegel [10]**

Although mathematicians and economists first developed decision theory, behavioural decision theory has come about as a result of psychology. Behavioural decision theory is largely concerned with the hypothesis of general rationality and aims to account for and explain human decisions. Normative decision theory concerns choices that a rational man should make in a given situation regardless of the decisions real men actually make. Descriptive decision theory concerns the choices real people actually make. Economists have been less concerned than psychologists with rationalising observed human behaviour and more concerned with choices that should be made to maximise profits or utility. Mathematicians, likewise, have usually been more concerned with the mathematical theory of rational decision making and the development of the mathematics of optimisation.

One of the key sources for modern decision theory is Raiffa [11]. He defined in very rough terms, the decision analysis process as:

1. List viable options available to you for gathering information, experimentation and for action.
2. List the events that may possibly occur
3. Arrange in chronological order the information you may acquire and the choices you may make over time.
4. Decide how well you like the consequences that result from the various courses of action open to you.
5. Judge what the chances are that any particular uncertain event will occur.

In Keeney and Raiffa [12], a more thorough logical process for decision making was proposed as:

1. Pre-analysis

   This involves identification of the problem and of the viable action alternatives available.

2. Structural Analysis

   This involves identifying what choices can be made now and what choices can be deferred. Also identifying what information needs to be gathered or experiments carried out to be able to make the choices. The decision-maker can order and begin to address these questions by constructing a decision tree.
3. Uncertainty Analysis

   The decision-maker assigns probabilities to the branches on the decision tree. This can be assisted by various techniques based on past empirical data, assumptions fed into and results taken from stochastic models, expert testimony and subjective judgements of the decision-maker.
4. Utility or Value Analysis

   The decision-maker assigns utilities to consequences associated with paths through the decision tree. The consequence associated with each path has to fully describe the implications of that path. The decision-maker then encodes his preference for the consequences in terms of utility number. The assignment of utility numbers to consequences must be such that the maximisation of expected utility becomes the appropriate criterion for the decision-maker's optimal action.
5. Optimisation Analysis

   The optimum strategy optimises expected utility. This strategy indicates what the decision-maker should do at the start of the decision tree and the best choice to make at every decision node along the decision tree.

This process is a good starting point for the support of decision making but it does have several limitations:

1. The process is based on a single decision-maker and takes no account of group decision dynamics or conflicting stakeholder views. In real life several people, even groups of people would be involved in the decision making process each would have their own perceptions of the risks involved and preferences for the final outcomes.
2. The process assumes that the decision-maker starts the analysis completely undecided and that the process of decomposing the decision reveals a set of answers that can then be scrutinised to ensure consistency. However the decision-maker may already have a decision made in his mind which can influence the way the decision process is carried out. If the purpose of the decision analysis is to reassure the decision-maker or communicate the solution to others, then that is acceptable. If the decision-maker is hoping to gain insight into the decision then he must start the decision process with an open mind.
3. The process assumes that the decision problem has already been identified and the viable alternatives specified. This however is a very crucial stage of the decision process and time must be spent ensuring that the problem is suitable for decision analysis and that all of the possible alternatives have been identified and addressed.
4. Many decisions that are considered involve multiple conflicting objectives, poorly quantified uncertainties, costs and benefits relating to various individuals and organisations, long term consequences and societal impacts. However this decision process does not aim to generate an "objectively correct" answer to the problem based on this array of complexities. Such a response could in many cases be impossible and if possible will be likely to be irrelevant. Instead, this process, despite being a formal analysis, is able to receive subjective evaluations for unquantifiable criteria, along with the objective values for quantifiable criteria. The

problem though, is often how to limit the number of evaluations required in an analysis.

5. This decision process has been aimed at supporting decisions both of a strategic nature (such as how much to invest in a certain field of research) as well as repetitive operational decisions (such as how much to charge for a certain product). Obviously, the strategic decisions are more complex to evaluate, but that is even more reason for decision analysis to be used to support it.
6. No mention has been made, as yet, in this decision process with regard to the implementation of the solution or post analysis of the decision results. This stage in the decision process should include aspects of how to communicate the right instructions to the right people, and identifying whom should be responsible for their completion. Also, though, this should include an evaluation of the results, both short term, (such as an immediate assessment of the fulfilment of objectives and a need to refine the evaluation process) and long term (such as monitoring of the long-term results of the decision). The result of both these requirements is the need to iterate the solution based on a sensitivity, to ensure that no new variables or alternatives come to light and that the final solution can be realistically implemented.

Comparing Keeney and Raiffa's decision process with the generic formulation of the decision problem, we are forced to ask whether the decision process does actually address all the entities (or issues) raised by the entity model. Table 1 below relates the entities to different stages in the decision process and identifies where there are gaps in the process.

Table 1: Relationship between the entities to different stages in the decision process

	Pre-Analysis (Identify problem & viable alternatives)	Structural Analysis (Identify timing of decisions & required information)	Uncertainty Analysis (Assign probabilities to each uncertain outcome)	Utility/Value Analysis (Assign utilities to decision consequences)	Optimisation Analysis (Select decision strategy based on optimum expected utility)
Management Group					
Asset Manager					
Other Stakeholders					
Structural Asset	☑				
Decision					☑
Alternative solutions	☑				
Perceptions			☑		
Preferences				☑	
Constraints					
Criteria				☑	
Type of Consequence				☑	
Probability and consequence		☑	☑		
Failure Event		☑	☑		
Initiating event			☑		

From this comparison, and as a consequence of the critique of Keeney and Raiffa's proposed decision process, we can see that issues such as the identification and inclusion of multiple decision makers (or stakeholders) into the decision process are required. The need to identify decision criteria (especially if multiple criteria are to be applied) and constraints are also required. Also missing is the opportunity to review the whole decision process to identify opportunities to refine the model. Clemen [13] suggested that this could be achieved through carrying out sensitivity analysis and model refinement at the end of the process.

A fully defined version of the decision analysis process is therefore proposed as shown in Figure 2.

Now that this process has been fully defined, it can provide all of the inputs identified by the entity diagram in Figure 1 and therefore ensures that all aspects of the decision problem are accounted for. The next important question is how to accomplish each of the stages of the proposed decision process and what methods are available at each stage. This proposed decision process has been used as a basis for the following review of risk based decision-making methods.

5.1 Problem Definition

The very first step in any decision analysis is to define the problem that is to be solved. This includes identifying the decision problem, defining the decision criteria the decision alternatives and the decision objectives. Also, once the decision problem has been identified, the key decision making group must be identified as must all other stakeholders in the decision, as these will affect the decision criteria, alternatives and objectives

5.1.1 Identify problem or opportunity

The decision making process starts with an individual noticing that either something is amiss or that some likely decision opportunity exists in the organisation or its environment. This awareness may not be founded on hard evidence; it could be based on little more than intuition [14]. This awareness may not result in immediate action but in a period of reflection, which according to Lyles [15] may only involve minor activity to make the problem go away. Following reflection, or because of the accumulation of evidence, the decision-maker becomes sufficiently convinced that a decision has to be made and the problem can no longer be ignored. The need for decision analysis, then only arises once a problem or opportunity has been identified that may be too complex or too important to solve by intuition. This decision identification is the central “node” shown in the entity diagram in Figure 1. A decision-maker may automatically realise that the first thing to do in evaluating a decision problem is to determine what the problem is. But how to go about defining the problem is more vague, especially if the problem is complex, full of conflicts, has a lack of definition and requires multi-disciplinary inputs. In addition, a review of previous decisions could reveal solutions that have been implemented at great expense that perhaps should never have been selected, had a thorough initial inquiry been made into the need that the solution was supposed to fulfil. It doesn’t take much insight to sense the waste, inefficiency and possibilities of significant failure for the decision-maker if a careful and deliberate inquiry into the problem is omitted.

The input to problem definition is a situation or set of stimuli that indicates that a problem exists. The decision-maker then has to explore what the true problem appears to be when extracted from the complex situation. Initially, the decision-maker seeks to identify and understand the basic need that the selected solution is to fulfil, from many different viewpoints in addition to his own. Very often, different people will have very different perceptions of what the true problem is. The definition of the problem would then have to be evolved through a series of discussions with the other decision-makers until a clearly defined problem can be presented.

Some examples of the types of situations that would give rise to the need for decision analysis could include:

- A problem in the allocation of funds to a selection of projects due to insufficient funds to cover all requirements.
- An opportunity to invest additional funds to obtain a favourable return, due to excess profits from business.

The types of problems that are encountered in Structural Asset Management (such as the management of bridges, pipelines, etc.) are:

- Selecting the best inspection, maintenance, or repair strategy (i.e. timing, method, and cost) for any particular structural component.
- Prioritising different components for inspection, maintenance or repair to give the optimum use of limited funds.

If the problem or opportunity to be solved is not clearly identified at this stage then confusion can occur later in the decision analysis process when further details are defined. These problems could be further magnified if more than one decision-maker is involved in the process.

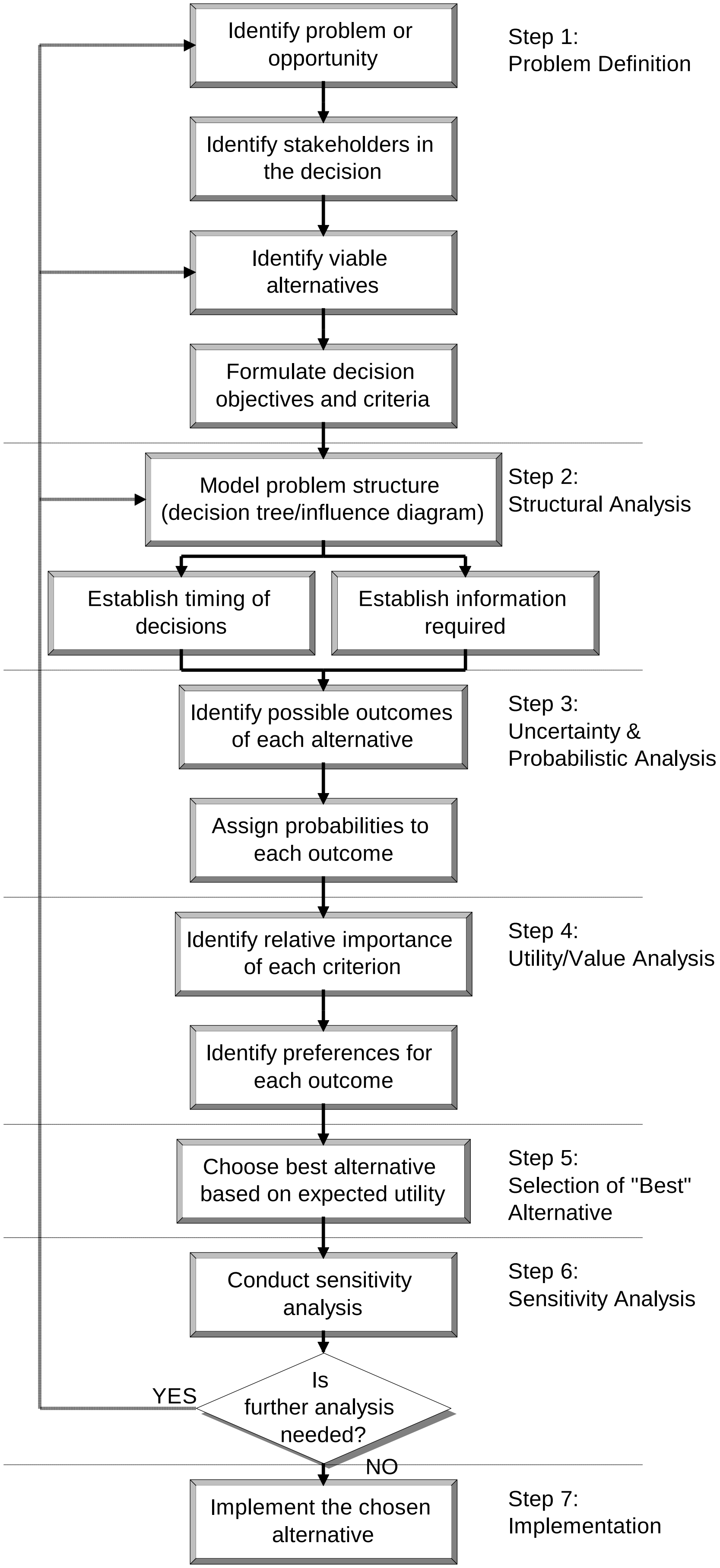

Figure 2: Outline of the decision process

5.1.2 Identify Stakeholders in the decision

In Keeney and Raiffa's work [12], a brief mention was made of the possibility of more than one decision maker being considered, or of other stakeholders having an interest in and an influence over the decision process. However, they chose to ignore this problem, as it would over complicate the theories. Von Winterfeldt and Edwards [16] also explicitly ignored the problem. However, I believe that this is a significant part of the decision making process as shown in the entity diagram of Figure 1, and therefore should be tackled as best as possible.

There are in fact very few decisions that can be reached by a single decision-maker with total disregard for others' views. Even where the formal procedures of an organisation dictate that an individual has responsibility for making the decision, the views of interested parties will usually need to be sought. On a more formal level a committee can be formed consisting of representatives of parts of the organisation who are expected to represent their departmental interests as well as contributing their own views. Committees may still, however be influenced by other external parties (or stakeholders) who would therefore need to be consulted. The result is that all members of the decision body (whether a committee or a set of independent advisors) will have different degrees of influence in the decision.

It is through the decision body that the organisation's objectives are interpreted and translated into operational evaluation criteria. This means that the individuals within the decision body not only make the choice itself but can also play an important part in controlling what options are considered and what information is considered relevant to how each option is evaluated. The overall objective of accounting for all appropriate decision-makers and stakeholders in a decision-making situation is to obtain ownership of the decision and commitment to its implementation from all affected parties.

When identifying the decision-makers and stakeholders, there can be a tendency to concentrate on the formal structure of an organisation. It is, however, necessary to identify informal decision-makers and stakeholder groups and to assess their importance. For internal decision makers/stakeholders, the indicators for power are derived from the level of the person in the company hierarchy, the recognition of individual leadership skills, the degree of control of strategic resources and the amount of relevant specialist knowledge. For those outside of the organisation, the key indicators are the degree of dependence of the organisation on external resources, the involvement of the external parties in implementation and the amount of relevant specialist knowledge. Some examples of the decision-makers to be considered in our example problem have already been discussed in Section 2.12. It is important for all stakeholders and decision-makers to be fully represented in the decision making process. Not all people with an interest in the decision making are experts with respect to all aspects of the problem situation, group decision making techniques can, therefore, be adopted to allow expertise, preferences and relative importance of each decision maker to be accounted for. The different methods of reaching group consensus in a decision making process can be broadly grouped into sharing, aggregating and comparing methods [17] and involve negotiation, joint scoring systems and voting techniques. Each of these methods could be appropriate in different situations depending on the strength of feelings of different stakeholders and their relative power.

5.1.3 Identify viable alternatives

The decision alternatives are the various courses of action between which the decision group must choose. The alternatives lie at the heart of decision-making because, unless there is more than one way to proceed, there is no choice and therefore no decision. The whole purpose of decision analysis is to select the best alternative from the set of available alternatives. All too often in decision analysis literature, the assumption is that the available alternatives are provided for the decision maker to choose between, or are at least obvious and easy to find. However, it is more common for the real problem in decision making to stem from a failure to produce sufficient feasible alternatives. De Bono [18] stated that there is a need to shift the emphasis in decision analysis from deciding between the alternatives to the generating of alternatives. I believe that there needs to be a good balance between the two as the following discussion illustrates. It is necessary, then, in any decision analysis problem to identify all of the alternatives available. This complete set can then be screened against rational criteria to bring the number of alternatives back to a manageable size. This screened set may also, be modified as the decision process progresses. This means that new alternatives can be generated either based on modifications of original alternatives or completely new.

There are two main types of decision problem: the “evaluation problem” and the “design problem”:

- The evaluation problem, is concerned with the selection of the best alternative from a set of discretely defined alternatives. This is “Multiple Attribute Decision Making” and is usually solved by some form of ranking method.
- The design problem, is concerned with the identification of the preferred alternative from a potentially infinite set of alternatives defined by a set of constraints. This is “Multiple Objective Decision Making” and is usually solved by mathematical programming.

Some decisions have alternatives that are obvious when the decision is defined. However, in other decisions, the precise nature of the alternatives is not immediately apparent. If this is the case, then for the design problem, it is straightforward to identify all possible alternatives, simply due to the way the mathematical programming solves the problem. For the evaluation problem, however, it is not so straightforward to identify all of the “right” alternatives.

Gardiner [19] identified the potential decision situation where the number of alternatives available for potential consideration is virtually unlimited and the number currently on hand for evaluation and decision making is comparatively small. He posed the question: “At what point do we stop looking for additional alternatives and make a decision based on what we know so far?” We still don’t know how well the alternatives on hand compare to those still undiscovered. This problem will strongly influence how seriously the final selection is taken. Gardiner proposed a method to overcome this by using Monte Carlo Simulation to produce a distribution of utility relating to the complete Decision Space of all possible outcomes. This was superimposed on to the values of utility calculated for the known options and therefore shows how the known options score in relation to all possible options.

However, the problem with this solution is that alternatives that are possible but not feasible could be produced in the decision space. This could result in too many alternatives to handle easily and may prove difficult to avoid or to recognise those that are not feasible. This could give a biased view of the alternatives that are known, causing too much or too little resource to be spent looking for more alternatives to produce a more balanced decision space.

Other techniques for generating alternatives include attribute listing, brainstorming and focused object linking [14].

Attribute listing is an analytical technique similar to the approach proposed by Gardiner, described above. It involves identifying the major attributes of the issue under consideration, such as size, cost, shape, etc and then altering each attribute in as many ways as possible. Each alteration or combination of alterations creates a potentially different solution. Resulting in a very large number of alternatives which may then become difficult to handle.

These solutions would then have to be screened for feasibility as described previously. Any decision that has to consider a large number of alternatives can mean that thorough evaluation of all alternatives is impossible in the available time. Screening narrows the range of alternatives again to a manageable number. The value of any screening methods increases inherently with its ease of use or speed in eliminating alternatives, however a good screening method should also be reliable in the alternatives that it keeps and those that it rejects. Any screening method, according to Walker [20] should possess two properties: 1. No very good alternative should be removed. 2. The number of alternatives remaining after screening should be relatively small. In addition a screening process should remove alternatives that are infeasible, unacceptable or dominated by other alternatives.

Brainstorming is probably the most well known idea generation technique and falls into the category of association techniques. The session involving an optimum of about 8 people is controlled by very precise guidelines. These include aiming for as many ideas as possible, recording all ideas, building on each other's ideas and banning all criticism and judgement. Without these guidelines the session can become unstructured and focused on one particular group of ideas.

A derivative of brainstorming is "brainwriting" [21], where participants write their ideas on paper instead of contributing them to a communal list. In the centre of the group is a separate list containing a few ideas generated in advance by the leader. Any member that runs out of ideas exchanges his list with the central one and continues to generate ideas on that one. It is suggested that each participant will be stimulated by ideas picked up from the centre list. Also participants will be able to concentrate better without being distracted or influenced by other members of the group. However this isolation could also restrict the degree of lateral thinking that takes place.

Focused Object Linking is a forced relationship technique that is based upon the establishment of relationships between normally unrelated ideas. This technique is particularly useful where new applications are sought for existing products, or new ideas for solving existing problems. On idea is fixed the other is either chosen randomly or from a pre-prepared list. Participants then try to find as many ways as possible to relate the fixed idea with the random one. The forcing of these relationships can lead to many new ideas.

Von Winterfeldt and Edwards [16] describe a method known as means-end analysis developed from artificial intelligence techniques by Pearl [22]. This method defines the problem as the difference between a desired goal state and the current state. Sub-problems are defined by the dimensions on which the current state falls short of the Goal State. The problem is then solved dimension by dimension by inventing actions sequentially to reduce the difference between the current state and the Goal State. This process has the potential of being quite thorough, but may also become tedious if there are many alternative increments in the solution.

Other “soft” operational research techniques such as Strategic Options Development and Analysis, Strategic Choice, Soft Systems Methodology, Robustness Analysis, Hypergames and Metagames can be used to help set down the alternatives (and criteria) for a particular problem [23]. Many different people’s viewpoints can be accounted for by use of cognitive mapping, decision trees, influence diagrams, payoff matrices, scenarios, strategic mapping and metaphorical thinking, [24] & [13].

In our example, we are considering whether a bridge that has been assessed to have insufficient capacity to carry the current traffic load should be

a) strengthened to full capacity
b) repaired to keep it at the current capacity but protected against further deterioration
c) left as it is with a load restriction enforced, to try to keep the loading below the assessed capacity.

There would obviously be many more alternatives in the real situation that would consider different methods of repair and different repair dates.

This decision scenario is of the evaluation type, as there are a discrete number of possible repair and strengthening options available. The problem in identifying all of the “right” alternatives would usually rely on the experience of the bridge engineers involved, but brainstorming type methods could introduce new alternatives not normally considered.

5.1.4 Formulate decision objectives and criteria

The final part of defining the decision problem is identifying the criteria on which the decision is to be based. The decision criteria are comprehensive and measurable representations of the decision-maker’s objectives used to describe the different alternatives. They can be objective (in this case the cost of repair and the risk of collapse resulting in death or injury would be considered) or subjective considering damage to the environment, disruption to traffic and local business if temporary restrictions are introduced.

The formulation of decision objectives helps the decision group in the decision process by:

1. Forcing the decision group to think in detail about the requirements for an acceptable solution.
2. Stimulating interest by providing a feeling of accomplishment.
3. Serving as a reference against which possible solutions can be measured.
4. Providing consensus on what is trying to be achieved.

Keeney and Raiffa [12] put this stage much later on in the decision process as part of the utility/value analysis. However, in my view the decision criteria should be defined at this earlier stage as part of the problem definition, before the problem is formally structured. The specification of objectives is likely to influence the structuring process.

For the design problem, it is likely that decision objectives and criteria will be known, and these will be used in mathematical programming to define the possible decision alternatives. However, for the evaluation problem, the decision alternatives are likely to be largely known, but the criteria on which the decision is to be made may not be clearly defined.

If the alternatives are known, then a “bottom-up” approach can be adopted to determine the decision criteria [1]. A number of different techniques can be used to analyse some of the alternatives, to compare them to see how they differ, or to identify the strengths and weaknesses of each alternative. These observations can then help formulate the set of important criteria on which the decision has to be made.

If, however, the decision alternatives are not known, but the objectives are, then the criteria will have to be defined based on achieving the decision objectives.

Once the decision criteria have been established, it is important to identify minimum standards on any of the criteria, which will act as constraints on any of the alternatives.

The criteria that could be considered for the bridge management example are cost, fatalities, injuries, traffic delays, social impacts, environmental effects and political impacts. It is based on these criteria that the decision objectives would be formulated. The decision objectives in this case are to minimise all of the criteria. The limits within which these objectives can be attained are defined by the constraints. The situation may arise where the decision alternatives, criteria and objectives are different for different interested parties (stakeholders) in the decision process. These could include the Highways Agency, the borough council, the local community, businesses and environmental pressure groups. Certain “soft operational analysis” techniques should be applied to obtain a consensus of the decision structure.

Before moving on to the next stage of the decision process a number of checks should be made to ensure the objectives have been satisfactorily defined. The objectives should be clearly defined, so that all in the decision group understand what is try to be achieved, they should also be consistent and agreed by all members of the decision group. Objectives should also be “sensible” [14], such that they are needed, they are practically achievable, relevant to the overall organisation objectives and they are measurable so that their achievement can be known. This is similar, but more subjective, to the "clarity check" proposed by Howard [25]. This concept was introduced to ensure that all stakeholders in the decision process have achieved absolutely clear definitions of the decision events and variables, before decision analysis starts. The clarity check considers the future and assumes access to all information concerning the future. The clarity check then asks whether it would be possible to say if the event in question (e.g. failure of a certain bridge component) had occurred. This basically means that if the problem is defined to such detail that specific numbers can be applied to the decision attributes, then the problem has sufficient clarity. The purpose of this exercise is to remove any vagueness in the decision criteria and alternatives and to ensure that all stakeholders understand the common and distinct perceptions held by each other concerning these values.

5.2 Structural Analysis

In most decisions it is necessary to break the main decision into smaller parts (this is the benefit of decision analysis). Depending on the decision problem in question this can mean subdividing the decision on different bases, depending on which most helps solve the problem. It could be that there are series of decisions to be made over time, where there are follow-up actions required after each sub-decision. Alternatively, at each stage in the decision process, the selection of one alternative could open up a whole series of other alternatives or events

These can be represented by a decision matrix, a decision tree or an influence diagram. A decision (or outcome) matrix is a method of modelling fairly straightforward decisions under uncertainty in such a way as to make explicit the options open to the decision maker, the uncertain events possible as a result of the decision and a simple decision rule to choose between the alternatives. This method is obviously only limited to a one off decision and is not able to take account of the sequential nature of decision making.

The decision tree format, however, enables the sequential decisions to be represented and the consequences of future decisions to be traced back to assess their influence on the present decision. In a decision tree, the alternatives and events are represented by the branches of a horizontal tree [26]. Figure 3 shows the decision tree for this example problem. It considers a bridge that is below the required strength where a decision has to be made between:

- Replacing the bridge with one of sufficient strength
- Allowing over loaded vehicles onto the existing bridge or
- Limiting the bridge to its assessed capacity.

Although decision trees are most useful for tackling complex, sequential problems they can also be useful for structuring simple ones. The decision tree shows the possible sequence of events with a notional time scale going from left to right. Earlier events and decisions are shown on the left with later ones shown on the right.

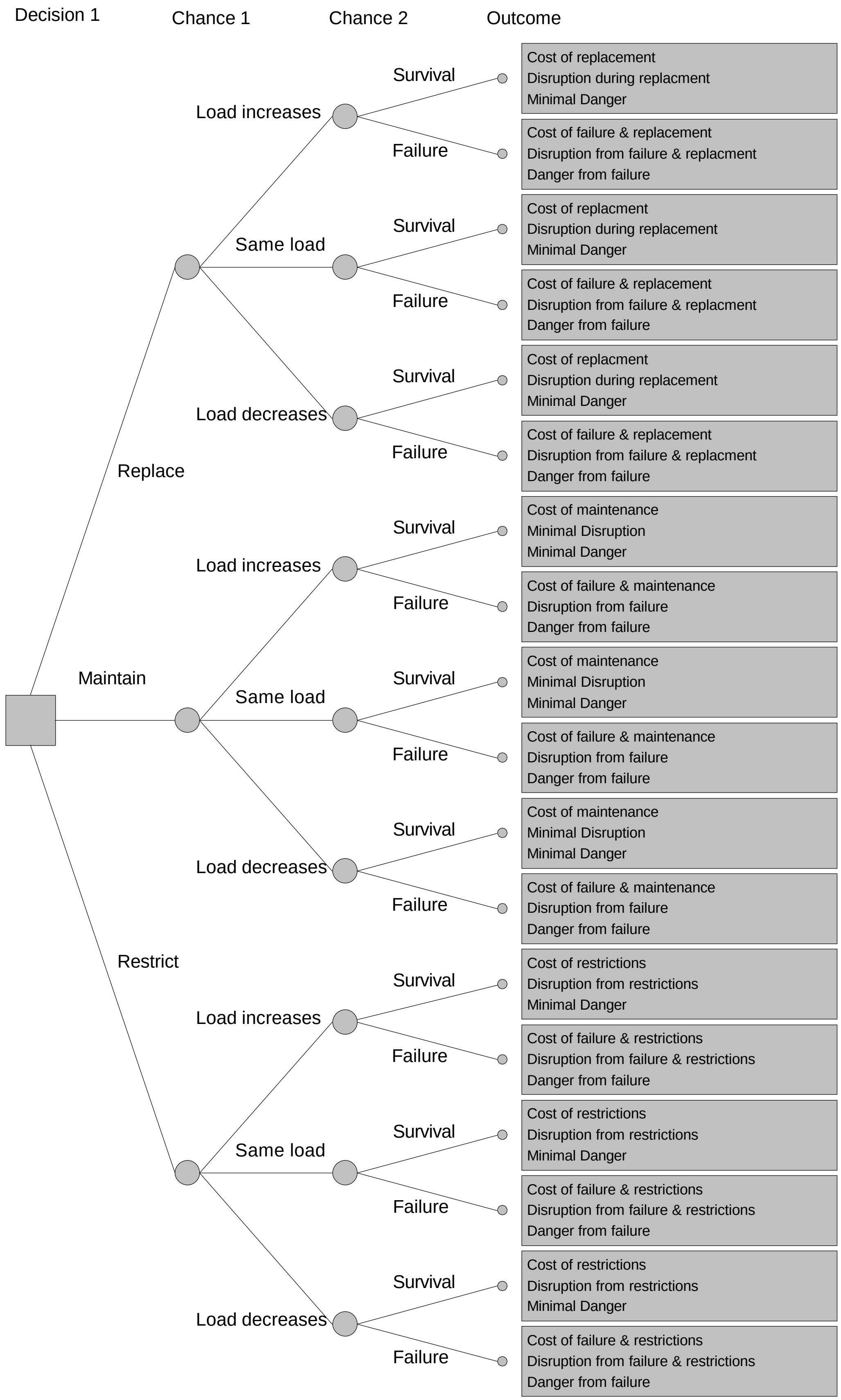

Figure 3: Example Decision Tree

An influence diagram, on the other hand, provides a simpler graphical representation of a decision problem. The elements of a decision problem: the decision to be made, uncertain events and the value of outcomes, are shown in influence diagrams as different shapes. These shapes are then linked with arrows to show the relationships among the elements [13]. The same example problem as before is presented in the form of an influence diagram in Figure 4.

Influence diagrams are particularly useful for the structuring phase of problem solving and for representing large or complex problems. Decision trees show more of the detail of the problem, but can, therefore get messy and out of hand [27]. Whichever method of representation is selected, should not affect the ultimate decision as either structure should be able to be converted to the other.

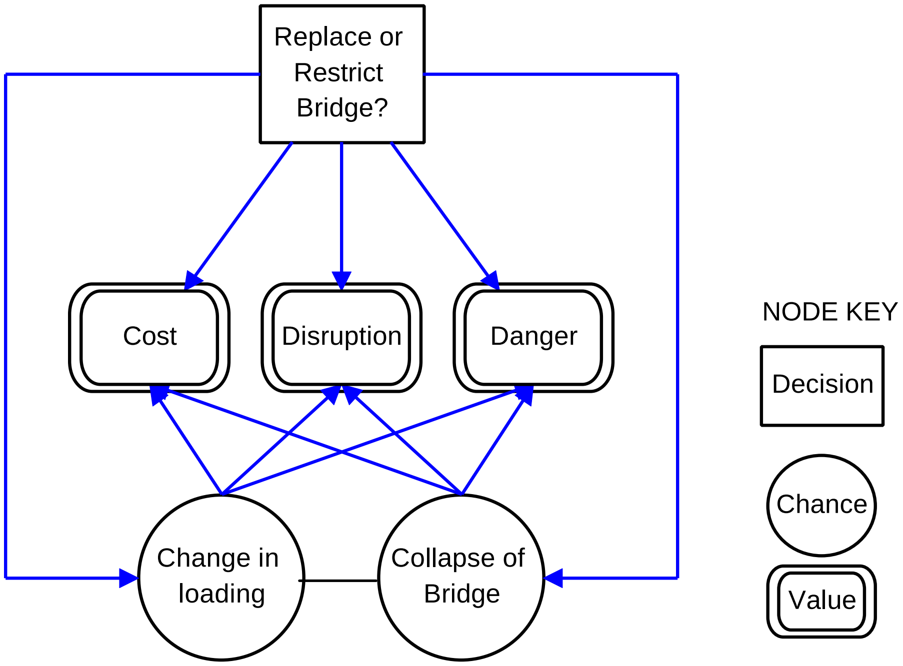

Figure 4: Influence Diagram of Example Problem

In addition the structuring process can be the time in which the decision criteria are defined in more detail. The Analytic Hierarchy process [28] helps the decision-maker to arrange the criteria into some sort of hierarchy so that the lowest level criteria are measures for the criterion in the next level above.

The structuring process, especially with influence diagrams, supports the decision-maker in the identification of all possible alternatives and all possible outcomes, and to see all the decision paths open to him. To the non-specialist it allows the structure of the risk scenarios to become divorced from the often confusing mathematical technicalities. If the decision is relatively straight forward, the decision tree or influence diagram can also be used to help solve the problem [13]. The values associated with each possible outcome and the probability of each possible outcome can be added to the structure. The "expected value" of each decision can then be calculated and based on this the best decision can be chosen. If however, the decision is very complex (e.g. involving multiple criteria) then it will be too complicated to try to solve with the use of a decision tree or influence diagram alone and multi criteria decision analysis methods will have to be adopted. Even so, the structuring process is still very useful in formulating the problem.

A number of computer programs have been developed to aid decision-makers in structuring decision problems. These guides aid the decision maker in the analytic formulation of the problem. A number of the most common tools are discussed in Section 5.7.

5.3 Uncertainty and probabilistic analysis

Since uncertainty is such a critical element of many decisions that are faced, it is necessary to take this into account in the decision modelling process. This, however, is one of the most difficult stages of the decision process. The differing degrees of certainty under which decisions have to be made are classified into the following four main conditions [3]:

1. Certainty:	The situation when the outcomes are certain plays a very small role in mathematical decision theory, since the decision criterion is so simple, however, certainty is a mathematical abstraction since real-life decisions (even those characterised by a condition of certainty) involve uncertainty. For example, it is considered, by most people, a certainty that when a light switch is switched on, the light will come on. Of course it is not 100% certain.
2. Rational competition:	The condition of rational competition occurs in “strategic decision making situations” and implies that any decision strategy acceptable to a fully rational decision maker would be equally apparent and acceptable to his rational competitor. The decision alternative recommended by the decision maker reflects this assumption. This is the basis of Game Theory [29].
3. Risk:	The decision maker is said to make his decision under the condition of risk if he is aware of the probabilities for the various states of nature resulting from the decision. When the condition of risk exists, each of the decision options can be interpreted as a gamble. However, it may be that the probabilities for these states of nature can not be calculated objectively from the mathematical theory of probability. In these cases, the decision maker may have “subjective probabilities” for the various consequences. It is these uncertainties of the occurrence of an event or the consequence of an event that have traditionally been handled by risk analysis.
4. Ignorance:	The decision maker makes his decision under the condition of ignorance if he recognises the possibility of more than one consequence for a decision, but is ignorant of which consequence is likely to occur.

There is very little mention of the formal handling of uncertainty within decision analysis literature. Traditionally simple subjective probabilities have been assigned to each of the chance nodes in the decision problem. The most detailed evaluation of uncertainties that is mentioned in the decision analysis literature is the risk assessment method originally described by Hertz [30]. The technique that he described can be summarised as follows:

1. Choose the uncertain variables that are considered to have significant bearing on the decision.
2. For each variable estimate the probability distribution which most closely reflects the decision maker's degree of belief as to the likelihood of the variable taking any value.
3. Choose the measure of outcome that will be used to evaluate the options.
4. Determine the function that relates the uncertain variables to the measure of outcome.
5. Randomly select a value from each of the distributions and combine them to determine a value for the measure of outcome.
6. Repeat (5) many times until a distribution of values for the measure of outcome is formed.
7. Repeat (1) to (6) for each option under consideration.

This method, from the quantitative risk assessment field of work, is a form of Monte Carlo Simulation, which will be described in more detail later. It rigorously accounts for uncertainty through the definition of subjective probabilities, but for that reason consumes a significant amount of computation time.

The literature concerning probability theory and structural reliability theory, does handle uncertainties far more thoroughly (although it is still possible to use subjective probabilities when required).

One of the objectives of the decision being made is to minimise the risk of failure of the structure. The main forms of the definition of risk were described in Section 4.2.4 where it was proposed that the definition of risk that be adopted in this risk based decision process be as shown below:

$$\text{Risk} = \text{Probability of failure} * \text{Consequence of failure}$$

The calculation of the probability of structural failure and the assessment of the magnitude of the consequences of failure includes the assessment and modelling of uncertainties. The uncertain parameters are then modelled as random basic variables described using appropriate probability distributions. These uncertainties arise from the inherent variability of loads and material resistance parameters, uncertainties in the deterioration over time, uncertainties in the analysis models used for determining the load effects and capacities, and the uncertainties in measurement and inspection techniques. In view of these uncertainties, it is possible that a structural component, such as a bridge crossbeam, could fail from an adverse combination of extreme values of the variables.

In a codified design or assessment, the safety of a structural component is ensured by using a number of partial safety factors to guard against extreme variations of the variables. Safety under a particular limit-state is checked using a design compliance equation of the form

$$F_C \cdot function\left(\frac{f_k}{g_k}\right) \geq g_{f3}\left(effects\ of\left(g_{fD} \cdot Q_D + g_{fL} \cdot Q_L\right)\right)$$

Equation 1

where, f_k is the characteristic material strength, Q_D is the nominal dead load and Q_L is the nominal live load. The uncertainty in material parameters is accounted for through the material partial factor γ_k for each material type, and separate partial factors γ_{fD} and γ_{fL} are used to account for the uncertainties in dead load and live load, respectively. The uncertainty in the evaluation of load effects (analysis uncertainty) is accounted for through the partial factor γ_{f3}. The reduction in the capacity of the component due to deterioration is accounted for either through the condition factor F_c or by calculating the component capacity using the net cross-section allowing for deterioration.

Structural reliability methods attempt to treat rationally the various sources of uncertainties involved in a design or assessment process. In a reliability analysis, the partial factors as in Equation 1 are not used. Instead, the uncertain parameters are modelled using appropriate probability distribution functions and the probability of failure of the component is calculated. If the computed reliability is higher than the specified “target reliability”, the component is considered to be acceptable.

There are three main types of uncertainty that could be encountered in a decision problem [31]:

Physical Uncertainty:	Due to the inaccuracies of manufacturing processes and the inherent variation of nature, there is inherent variability in physical quantities. These could include variability in dimensions, loads, and material properties. This variability can be described in terms of probability distributions but only after examining sample data (e.g. Counting traffic, measuring strengths, etc.) However, because of the cost of taking measurements, uncertainty will still remain, this is statistical uncertainty.
Statistical Uncertainty:	Statistical uncertainty arises from inferring probability distributions from sets of sample data. But since it is almost impossible to fit a known distribution exactly to the sample data, inaccuracies arise. This inaccuracy is reduced as the number of samples increase, but is never completely removed. This therefore, is solely a result of lack of information.
Model Uncertainty:	Predictions of many different kinds make use of mathematical models that related required output quantities to the available input quantities. These models could be based on intimate understanding of the physical relationships between the inputs and outputs, or they could be based on

empirical data. Either way, they may be accurate enough, but never perfect, at some stage they will be based on some simplifying assumptions. These inaccuracies can become very significant and therefore must be accounted for.

The reliability analysis approach is closely linked to the “limit-state” concept. For each limit-state (or failure mode) of a structural component (e.g. bridge crossbeam), a separate reliability analysis is carried out to evaluate the probability that this limit-state will not be reached. For the calculation of the probability of failure it will be necessary to define failure modes for the structure in question. For example a reinforced concrete bridge crossbeam could have failure modes for bending, shear and loss of bond capacity. Appropriate loading and resistance models will have to be developed for each failure mode and each uncertain variable within these models will have to be modelled as a random variable. The probability distributions associated with each random variable should be based on a large sample set of data (such as traffic counting, material strength tests, etc.). For some variables this will not be possible, so subjective probability distributions will have to be defined based on similar data and experience.

The results of the separate reliability analyses can be combined, if necessary, to calculate the overall reliability of the component. In analogy with the design compliance equation, the “safety margin equation” used in reliability analysis can be expressed as

$$Z = function\left(f_k\ ,\ \mathrm{g},\ d\right)\cdot B_R - \left(effects\ of\left(Q_D + Q_{SDL} + Q_L\right)\right)\cdot B_Q$$

Equation 2

and the probability of failure is calculated as

$$p_f\ = Probability[Z \le 0]$$

Equation 3

where, Z is the “safety margin” and p_f is the probability of failure. The resistance of the component is evaluated as a function of the uncertain material parameters f_k, geometrical parameters g, and deterioration parameters d, which are considered as random “basic variables” and described using appropriate probability distributions. On the loading side, the dead load Q_D, the super-imposed dead load Q_{SDL}, and the live load Q_L are treated as random variables. In addition, the variables B_R and B_Q have been introduced to model, respectively, the uncertainty in the capacity calculations and in the analysis method used for calculating the load effects. A number of efficient techniques are now available for calculating the probability of failure as expressed in the above equation.

The probability of failure as expressed in Equation 3 can in principle be calculated using any one of the following three methods:

- Numerical integration
- Monte-Carlo simulation
- FORM/SORM methods

Direct numerical integration is only feasible if the number of basic variables is less than about 5. Monte-Carlo method becomes computationally expensive if the failure probabilities are very small, which is typical of bridge components. In recent years a number of techniques such as “importance sampling”, “directional simulation”, etc. have been developed to improve the efficiency of the simulation method. The third category of methods are approximate analytical methods designed to compute the failure probability very efficiently, and have become the most widely used methods in recent years. In a First Order Reliability Method (FORM) a linear approximation to the actual non-linear limit-state function is used, while in a Second Order Reliability Method (SORM), a quadratic approximation is used [31] & [32]. This has been carried out by the author using a commercial structural reliability software, SYSREL [33].

The probability of failure (for each failure mode) will have to be calculated for each alternative identified in the decision tree, so should take into account either the reduction in loading, the increase in resistance or the continued deterioration of the structure. The exact effect of each of these measures will be unknown, so these uncertainties will also have to be accounted for.

The analysis gives the probability of failure p_f and the “reliability index” β which is related to p_f through,

$$p_f = \Phi(-b)$$

Equation 4

where $\Phi(.)$ is the cumulative distribution function of the standard normal variable.

A reliability analysis also provides “sensitivity factors” which express the relative importance of the uncertainty in each basic random variable to the computed probability of failure of the component. In addition, the gradients of the reliability index with respect to the mean value $\partial\beta/\partial\mu i$ and the standard deviation $\partial\beta/\partial\sigma i$ for each random variable Xi can also be calculated. These gradients are normalised by the reliability index and are often termed as “elasticities of the mean and the standard deviation”. The analysis also gives the “most-likely” combination of values of the variables that would cause the failure of a component.

For the evaluation of the magnitude of the consequences of failure, all the different types of consequences must be identified. The most common consequences to consider are financial, injury, fatalities and environmental consequences. However other consequences that can be accounted for subconsciously include social, political and commercial consequences, these, are not normally accounted for explicitly. It is very difficult to predict the magnitude of these consequences and can be difficult to identify a useful scale on which each consequence is measured.

Traditionally, each consequence is converted to a financial scale which causes problems when trying to put a financial value to a life, the environment, society, etc. Multi-criteria decision analysis means that all these consequences don’t have to be converted to a common scale, but can be assessed in their most convenient terms.

Uncertainties can then be accounted for by describing each consequence as a probability distribution in these terms. The distributions can either be derived from historical data or if this is unavailable then subjectively based on “expert” opinion.

A distribution representing the risk of structural failure for each consequence can then be derived. These individual risk values can be represented on each branch of the decision tree [34] but they should not be combined into an overall risk of failure at this stage, until after the utility/value analysis has been carried out.

If such a detailed assessment is not required, or an initial view of the problem is required before detailed analysis, then a simplified risk scoring system can be used similar to that described in Shetty et al. [35].

5.4 Utility/Value Analysis

Once the decision problem has been formulated, it is necessary to evaluate each alternative in the light of the decision criteria, so that the “best” alternative can be chosen.

There are two types of preferences to be considered in the decision analysis, one is the decision makers’ order of preference between the different decision criteria, i.e. is cost more significant than safety? This type of preference can be handled by ordering or weighting the decision criteria. Therefore this type of preference will be called weighting.

The other type of preference is the decision makers tolerance of the consequences of his/her decision. Traditionally, this is defined as two separate types of preference, namely, value and utility. Utility is the preference between a sure consequence and a gamble (e.g. in simplistic terms, how much the decision-maker is prepared to sell a gamble for). This then accounts for the degree of risk aversion of the decision-maker. Value, however, is the preference for gain or loss of a sure amount compared with a different sure amount (e.g. how much worse is a cost of £1m than £1k, is there a linear or non-linear relationship to the decision maker’s value of money and the direct value of money). The standard argument states that the procedures used to develop a value function will not lead to the same utility function, although the evidence in the argument is scarce. Von Winterfeldt and Edwards [16] state that the distinction between the two types of preference function is spurious as:

1. Nothing is certain, so a value function applied to a sure thing is really applied to a low risk gamble.
2. Risk aversion, easily accounted for in utility functions can also be explained by marginally decreasing value functions.
3. Repetitive choices tend to eliminate risk aversion.
4. Error and method variances within value and utility measurement procedures tend to overshadow the subtle theoretical differences.

I believe that the last point is the most significant in this matter and that a value/utility function can be created for each measure accounting for the level of uncertainty in that measure. Therefore from now on the term utility will represent what has formerly been know as value and utility.

The two types of preferences: utility and weighting are inter-linked and techniques for modelling both of these types of preferences are discussed below.

For the two types of decision problem (evaluation and design), there are different methods for assigning preferences, so these will be discussed separately.

5.4.1 Evaluation Problem

There are two distinct types of approach for the evaluation problem: aggregate value function approaches and outranking approaches [1].

5.4.1.1 Aggregate Value Function Approaches

Aggregate value functions have been largely developed and applied in the USA and cover four main forms of approach:

- Multi-Attribute Utility Theory
  This complex technique attempts to jointly model the preferences between the decision criteria and the preferences between the consequences. This involves eliciting preference structures from the decision maker by considering pairs of preferentially independent attributes on the condition that the other attributes are held fixed. For each pair of attributes considered, a relationship is derived from detailed questioning, to show how much of one attribute the decision maker is willing to give up for a certain amount of the second attribute at different values of the first attribute. This method has the potential of deriving very detailed relationships (utility functions) between attributes allowing the desirability (or acceptability) of risks to be compared. However, the questioning process required to arrive at these relationships is so demanding that many decision-makers have trouble answering the questions posed. [12]
- Simple Multi-Attribute Rating Technique
  This technique is about as simple as multi-attribute utility measurement gets. It derives multi-attribute utilities (reflecting the “attractiveness” of a gain or loss in an attribute) for the decision criteria based on simple rating procedures. The technique consists of ten simple steps identifying the important criteria and then ranking and weighting the criteria with suitable ratios. For each criteria a scale of 1-100 is derived for the range of possible outcomes (utility) and each alternative is scored on that scale. The total utility for each alternative is calculated by a simple additive aggregation rule that allows the attributes to be traded off and the alternative with the highest total utility is selected. Although lacking in theoretical elegance, this method is easily taught and simplifies the derivation of values by considering one criteria at a time. [36].
- Inverse Preference Methods
  These are methods which, rather than applying preferences directly to the decision criteria (which can be quite difficult), apply them to a sample set of alternatives and infer the preferences for the criteria from them. Holistic judgements are made about the value of the alternatives. The decision makers consider a number of alternatives described in terms of the selected criteria and indicate their preferences by ranking or assigning a score to the

options. Mathematical programming is used to determine a weighted value function consistent with the decision maker's ordering. The function is shown to the decision maker, who can decide how appropriate it is. If necessary the process can be iterated until a suitable value function is achieved. Examples of this method are PREFCALC developed by Lagreze and Shakun [37] and POLICY developed by Rohrbaugh and Wehr [38].

- Analytic Hierarchy Process

  This technique derives weights which reflect the relative importance of the different criteria. The criteria are arranged into some sort of hierarchy so that the lowest level criteria are measures for the criterion in the next level above. Pair wise comparisons are used to elicit an individual's preferences for each criteria in each level of the hierarchy. A scale from 1 (equally preferable) to 9 (absolutely dominant) is used to indicate the strength of dominance of one criteria over another. This can be carried out in the form of a questionnaire. From these questionnaires, a pair-wise comparison matrix can be constructed. The ratio weights, summing to 1 are the normalised eigenvector based on the principal eigenvalue. A by-product of this calculation calculates a consistency index for the decision maker's preferences. This method allows the decision maker to define his/her preferences in a manageable and rationale manner. [28]

  An extended version of the method was developed by the author to help with these comparisons, in a project to help prioritise a large number of bridges for repair and strengthening work. This involved producing a series of decision scenarios that changed the values of pairs of criteria in each scenario, the decision maker was asked to select which alternative they would choose. As the scenarios changed, there would come a time when the decision maker would move from selecting one alternative to selecting the other. This crossover point would then infer the value of dominance of one criterion over the other. This would be repeated for all pairs of criteria until a full pairwise comparison matrix could be completed.

  This method was used with four different decision makers (all borough bridge engineers) involved in the same decision making process, all were reasonably comfortable with answering the questions, despite being asked to compare criteria they had never thought of comparing before. Surprisingly, too, all four decision makers arrived at very similar weightings for most criteria despite very different cultural and political viewpoints. Baillie's [39] Modified Median Consensus Method was used to combine the preference weightings from all decision makers into one weighting vector.

At the end of the utility/value analysis, each consequence of each alternative should be converted to a common (utility) scale. The risk of each consequence should be accounted for as a probability distribution and then weighted according to the relative importance of each type of consequence (criteria). This should result in a table that looks something like that shown in Table 2.

Table 2. Calculation of the weighted probability distribution in terms of the utility for each criterion.

Alternative	Criteria	Total

	Cost	Social	Injuries	
1. Limit Load	$C_1 = w_c*f_{xc1}(U_{c1})$	$S_1 = w_s*f_{xs1}(U_{s1})$	$I_1 = w_i*f_{xi1}(U_{i1})$	$R_{T1}=C_1+S_1+I_1$
2. Repair	$C_2 = w_c*f_{xc2}(U_{c2})$	$S_2 = w_s*f_{xs2}(U_{s2})$	$I_2 = w_i*f_{xi2}(U_{i2})$	$R_{T2}=C_2+S_2+I_2$
3. Strengthen	$C_3 = w_c*f_{xc3}(U_{c3})$	$S_3 = w_s*f_{xs3}(U_{s3})$	$I_3 = w_i*f_{xi3}(U_{i3})$	$R_{T3}=C_3+S_3+I_3$

Where

- U_{ai} is the utility of criterion, a, for alternative i.
- f_{xai} is the combined probability distribution for alternative, i of the probability of failure and the probability of the consequence, a, given failure.
- w_a is the derived preference weighting for criterion, a.
- R_{Ti} is the distribution representing the total risk of failure for that alternative.

5.4.1.2 Outranking Approaches

The outranking methods, principally developed in France and Belgium, differ from the aggregate value function methods in that they do not consider that all alternatives can be compared. In some situations, the theories maintain, the decision maker will be unwilling or unable to compare some options. The output of these methods is not a value function for each alternative but an outranking graph indicating preferences, indifferences and incomparabilities. The two most dominant groups of outranking methods are ELECTRE IV developed by Roy [40] and [41] and PROMETHEE developed by Brans, Mareschal and Vincke [42].

- The ELECTRE IV method
  Each pair of alternatives is initially compared to determine the strength of the outranking of each alternative (e.g. alternative 1 strongly outranks alternative 2). Two groups are identified, those which are strongly outranked by any particular alternative and those that are weakly outranked by any alternative. Each alternative is then qualified by the number of alternatives that are outranked by that alternative minus the number of alternatives that outrank that alternative. The alternatives are then “distilled” by taking the highest qualifying alternative as number one, removing it and re-qualifying the remaining alternatives, then taking the next highest qualifying alternative out and re-qualifying again, and so on until a distilled order is achieved. This can then give the final ranking. This is a very time consuming and complex process that is not very attractive to many decision makers.
- The PROMETHEE Method (Preference Ranking Organisation METHod for Enrichment Evaluations)
  This method includes two phases: the construction of an outranking relationship for the decision space and an exploitation of the relation to maximise the decision criteria. In the first phase, a valued outranking relation based on each criterion is considered, a preference index is defined and a valued outranking graph, representing the preferences of the decision maker is obtained. The exploitation of the outranking relation is realised by considering for each action a degree of preference over each other alternative for each criterion. A partial pre-order is obtained in PROMETHEE I, or a complete pre-order with PROMETHEE II. This

> considers the set of all possible actions and can be proposed to the decision maker in order to achieve the decision problem.
>
> In tests carried out by Brans, Vincke and Mareschal [42] the influence on rankings when small deviations in preference values are introduced, were considered for the PROMETHEE and ELECTRE methods. It was shown that PROMETHEE is more stable than ELECTRE in that small deviations do not affect the rankings while large deviations do. It was also found that the more extreme the disagreement between criteria the less stable are the evaluations.

Sometimes, the choice between the use of an Aggregate Value Function method or an Outranking method may just be a small part of the overall analysis, at other times the issue could become far more significant and be the focus of substantial discussion. The chosen method will be more likely to be selected based on the requirements and availability of input information rather than on the output information that is provided, as all methods give very similar outputs. The rigour of the analysis however, depends on the availability of input information and could therefore affect the confidence of the decision maker in the final results.

5.4.2 Design Problem

As described earlier, the design problem differs from the evaluation problem in that the alternatives are not explicitly defined, but implicitly defined by constraints. Most methods that are used to solve these problems involve mathematical programming of some sort. Goal programming and multiple objective programming are the most widely used approaches. Objective functions are defined according to the objectives and preferences of the decision maker, these could be, for example to minimise cost, maximise capacity, etc. These objective functions are then optimised according to the set of constraints. If required, penalty functions can be defined instead of constraints, where alternatives can exceed certain values of the criteria but at a cost.

5.5 Selection of "best" alternative

5.5.1 Evaluation Problem

There are several methods available for selecting the best alternative once the attributes have been scored and weighted. In the analytic hierarchy process, once the weighted scores for each attribute have been determined, they are summed for each alternative as shown in the final column of Table 1 and the alternatives are then ranked according to their total weighted scores. The "best" option would be the one with the highest score.

Other methods are available, although they don't take a direct sum of the score but look at the scores for each attribute individually. One of the most common methods that makes use of informal preferences is the Expected Value Principle [43], this is a very simple view of risk and was criticised by Howard [44] who believed that expectation does not capture the way most people think about risk. He proposed that for most people it is the standard deviation that represents the risk, not the mean or expected value. It is true that the highest expected value is very often not the preferred option for many people as it can still represent a very high probability of a bad outcome despite a very low probability of a very good outcome. Also, the consequence space is sometimes not continuous and so the outcome will either be very good or more likely be bad. However, expected value remains a concept that is straight forward to calculate and explain which can make it a very popular method in every day risk assessments. Another method of evaluating risk is to determine a certain equivalent of that risk, i.e. how much would be paid to be free from the given risk. This however, can be very difficult to quantify consistently and needs to be carried out for every risk that is being considered. Other "informal methods" for evaluating risk alternatives include:

- The Dominance theory [45]
- The Criterion of Pessimism [46]
- The Criterion of Least Regret [47]
- The Criterion of Rationality [48]
- Lexicographic ordering [49]
- The Efficient Frontier (which originates from the Capital Asset Pricing Model, [50])
- Use of artificial constraints
- Use of variable, linear-weighted averages.

These methods have been well documented in the early text on decision theory, so further description is not necessary here.

5.5.2 Design Problem

The objective functions created within the design problem are usually solved by using calculus-based methods to find local extrema, solving the set of non-linear equations that result from setting the gradient of the objective function to zero. However, this approach is not entirely robust as the optima sought are the best in a neighbourhood of the current point. If the search starts in the wrong place then it could miss the main peak and converge on a lower peak. If this occurs, further improvement can be sought by randomly restarting the search, although, this of course is still unreliable.

Enumerative search techniques are another option, this algorithm will look at objective function values at every point in the space, one at a time. This method is very simple and is unlikely to miss an optima, however, it is very inefficient.

A third method that has increased in popularity is random search, yet these are little better than enumerative methods in terms of efficiency, if a reasonable degree of confidence is required in the final result. A different type of random choice that is proving more successful if applied carefully, is the use of genetic algorithms [51] and [52]. These are search algorithms based on the mechanics of natural selection and natural genetics. They combine survival of the fittest with a structured yet randomised search algorithm. In every iteration, a new set of alternatives is generated using parts of the fittest of the old set and adding a new part occasionally for good measure. They efficiently exploit historical information to speculate on new search points with expected improved performance.

More recently interactive methods have been developed where the decision maker is "taken on a tour" of non dominated alternatives. At each stage, the decision maker identifies preferences until the most preferred alternative is identified.

5.6 Sensitivity Analysis

Sensitivity Analysis answers the question “What matters in this decision?” No “optimal” sensitivity analysis procedure exists for decision analysis [13]. But, sensitivity analysis should be an integral part of the decision modelling process. The flow chart in Figure 2 shows how sensitivity analysis can feed back information to different stages in the decision process, even right back to the identification of the problem and the identification of the problem objectives. The question to ask at this stage is “Are we solving the right problem?” The answer doesn’t require quantification but in does require careful thought. This should protect against a decision treating a symptom rather than the cause.

Sensitivity analysis can also be carried out in the context of the problem structuring, this could result in requiring a more complete set of possible outcomes, or a more detailed description of the outcomes. It could even result in the problem being represented in a completely different way.

The third way that sensitivity analysis can be of assistance is to determine which variables are important and therefore which uncertainties would be best refined.

Finally sensitivity analysis can be carried out to determine the diversity of individual decision maker’s preferences, the effect of those preferences on the consensus weightings and the sensitivity of the final outcome to any conflicts that may have arisen.

Certain graphical techniques have been developed within decision analysis to help determine the relative importance of different variables.

5.6.1 Tornado Diagrams

This diagram shows how much the value of an alternative can vary with changes in a specific quantity [25]. The mean values of each attribute for that alternative are assumed as the base value, then each variable is evaluated at points between its minimum and maximum to determine how much it would change the final decision value for that alternative. As an illustration, consider the simple example presented before, the effect on the total cost of the uncertainty in the loading, the strength and the probability of injuries, is considered in the context of the alternative of restricting the bridge. This could be shown as in Figure 5. This shows that the cost is most sensitive to the loading on the bridge.

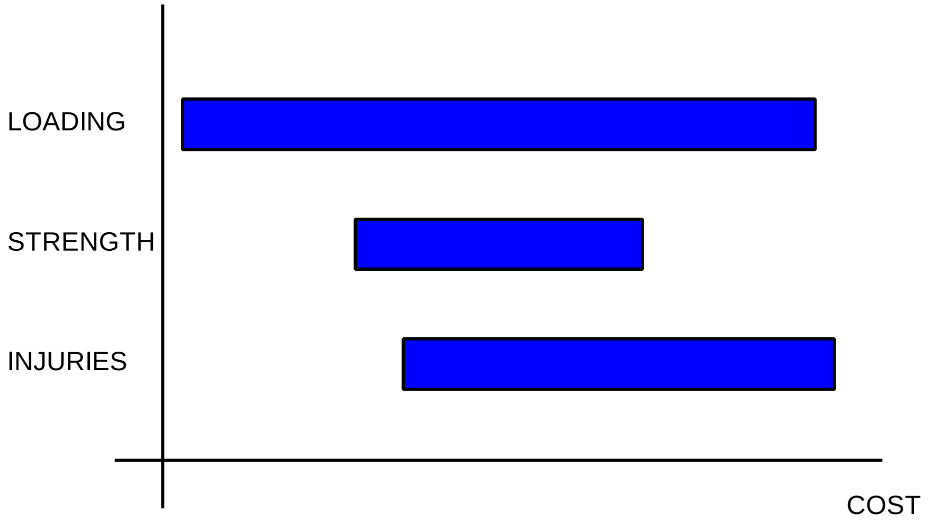

Figure 5: Example Tornado Diagram

5.6.2 Two Way Sensitivity Analysis

The Tornado diagram can provide insights into what happens when only one variable changes at any one time. We may want to consider, though, the impact of several variables at one time. A graphical technique exists to allow the interaction of two variables to be considered. This is called a Two-way Sensitivity Graph and is shown in Figure 6 for the same example problem considering the sensitivity of cost to the loading and the number of injuries [13]. The diagram shows a rectangular space that represents all of the possible values that these two variables could take. A relationship can then be plotted showing how the variation of these two variables affects the total cost, this is a line of constant cost.

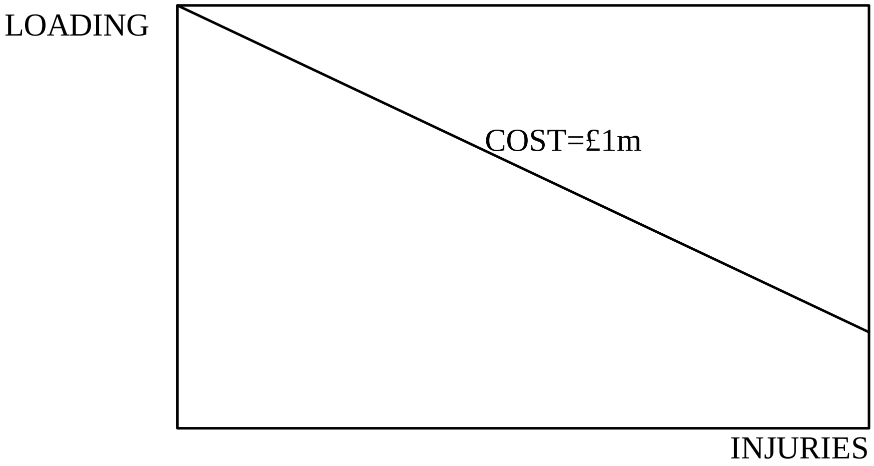

Figure 6: Example Two Way Sensitivity Graph

5.6.3 Strategy Regions

It is possible to construct a two-way sensitivity graph for two uncertain variables, which can show for a decision between two alternatives, under what conditions of uncertainty, the expected value of deciding alternative 1 is greater than the expected value of deciding alternative 2 [13]. An example is shown in Figure 7. This can help indicate when different strategies are optimal. The benefit of this plot comes when the decision maker is uncertain of the probability of the two uncertain variables, the strategy region graph can provide guidance in determining how much effort is needed to model uncertainty in the decision problem. However, for large number of uncertain variables and a large number of alternatives, the number of graphs that would have to be plotted would become unmanageable.

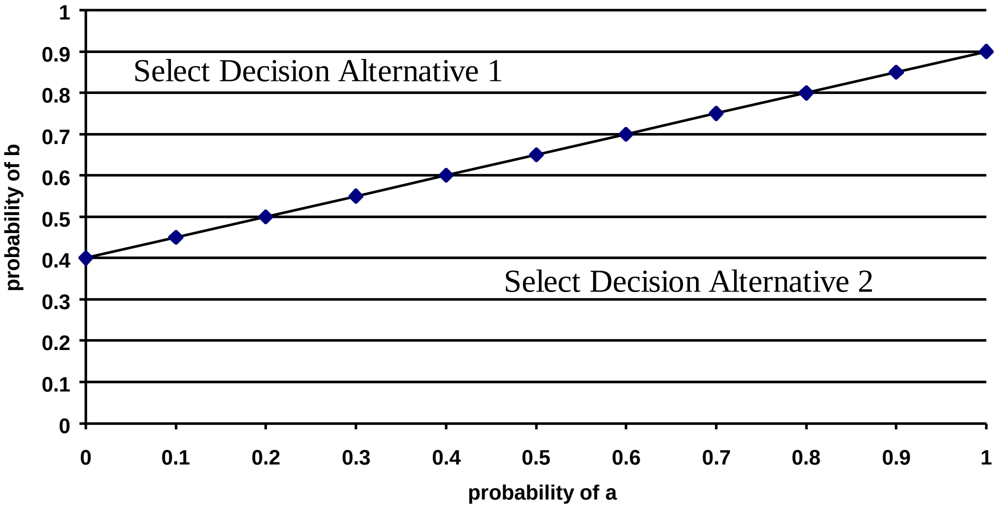

Figure 7 Example of Strategy-Region Graph

5.6.4 Alpha Value Sensitivity Analysis

On a more detailed level, it is possible to evaluate the relative importance of the uncertainties in each of the variables used as inputs in the structural reliability calculation. First Order and Second Order reliability analysis methods inherently provide “sensitivity factors” which express the relative importance of the uncertainty in each basic random variable to the computed probability of failure of the component [32]. This then allows the decision maker to identify the potential benefit of obtaining additional data to refine the most important uncertain variables.

5.6.5 Multi Dimensional Scaling

Sensitivity analysis can be carried out to determine the diversity of individual decision maker’s preferences, the effect of those preferences on the consensus weightings and the sensitivity of the final outcome to any conflicts that may have arisen. Multi-dimensional scaling is a technique that produces a map showing the relative positions of a number of items using data on the distance between each pair of items. Using the weights produced by each of the decision makers interviewed it is possible to calculate the total distance between any two decision makers, this can be repeated for all decision makers building up a map to show the relative position of all decision makers. The consensus set of weights can also be added to the map to investigate the existence of a true consensus rather than a purely mathematical one. Finally the different decision makers can be grouped together using a technique known as cluster analysis to allow identification of any clustering and any possible reasons behind it. This can help check that all decision makers were interviewed in the same unbiased manner.

5.7 Decision Support Software

The advent of modern computer systems and large databases has served as a starting point for new challenges in decision making. The need for information access and processing is a critical part of the decision making process, but it is only recently that the tools have become available that are able to cope with the volumes of data and complex analysis methods. A number of computer programs have therefore been developed to aid decision-makers in structuring decision problems, in eliciting probabilities and values, and in sensitivity analysis. These guides aid the decision maker in the analytic formulation and evaluation of the problem. The following discussion describes some of the most popular decision support tools, their capabilities and their limitations.

EXPERT CHOICE was one of the first computer based decision tools to be developed by Decision Support System, Inc in the early 1980s and is a multi attribute decision support program based on Saaty's analytic hierarchy process [28]. The structuring module provides a framework for collecting ideas (e.g. pros and cons of alternatives) and transforming them, by developing criteria and organising the criteria into a hierarchy, into an AHP model. This method for conceptualising an AHP model is only suitable for small problems and becomes cumbersome as the problems increase in size. The evaluation and choice module then can be used for pairwise comparisons, solution synthesis, sensitivity analysis and report generation. In small problems the criteria at each level in the hierarchy are pairwise compared against each other, but this becomes impractical with larger problems, so an alternative method is provided, whereby the alternatives are compared against a set of standards instead. This approach reduces significantly the number of comparisons required. The Inconsistency Ratio is also calculated and recommendations for improved consistency are made, under user control.. For quantitative criteria, it is possible to enter data values (e.g. costs) directly. Probabilities can also be input. The result of solution synthesis is an overall score for each alternative, which is then presented graphically. Sensitivity analysis can be used to consider the sensitivity to criteria priorities using by several different graphical modes.

CRITERIUM DECISION PLUS, developed by InfoHarvest, is a package that implements two approaches to multi attribute decision making. It uses both Saaty's [28] Analytical Hierarchy Process (AHP) and Edwards' [36] Simple Multi Attribute Rating Technique (SMART). The focus of the software is to help the user fully understand multi-criteria analysis and the effect of uncertainty in the outcomes on the preference over decision options. A brainstorming module allows complex models to be quickly set up and then automatically converted into a hierarchy that can then be modified by the decision maker. The software aids the decision maker in assigning relative importance to criteria in a consistent manner (by use of numbers, bar graphs and words) and rating the alternatives against the criteria. The weighted score of each alternative indicates how well they meet the decision criteria. Graphical presentations of the results allow the decision maker to analyse the decision for reasonableness, robustness and sensitivity to trade-offs. The decision maker can also apply probability distributions to define uncertain data, which means that not only is the best alternative to meet the criteria identified, but also how likely that alternative is to be truly the best choice. The outcomes based on the assigned uncertainties are overlaid the results based on a deterministic assessment to give a graphical representation of the impact of uncertainty on the decision. Sensitivity analysis of the uncertainties helps the decision maker identify which uncertainties to reduce. This package is apparently as robust as EXPERT CHOICE and has the added advantage of being able to choose between SMART or AHP for evaluating importances.

Other packages that allow the structuring of alternatives and the definition of criteria weights through AHP and/or SMART are HIPRE3+ by EIA, LOGICAL DECISIONS by Logical Decisions, ALIAHTHINK by Aliah. Although these do not have the added benefit of uncertainty analysis.

A more simplistic family of decision software tools allows the definition of decision problems through decision trees and influence diagrams, based on single attribute decision making and Expected Value as the decision criteria. Some of these packages have very powerful uncertainty analysis tools such as ANALYTICA by Lumina, CRYSTAL BALL by Decisioneering, DEFINITIVE SCENARIO by Definitive Software, NETICA by Norsys and DECISION PRO by Vanguard Software. The tools that are based purely of subjective probabilities and expected value criteria include PRECISIONTREE by Palisade, DPL (Decision Programming Language) by Applied Decision Analysis and DATA by TreeAge.

Recently, due to the further development of computer technology, decision support software houses have started to produce group decision support systems such as TEAM EXPERT CHOICE by Decision Support System, Inc and DECISION EXPLORER by Banxia. These use group brainstorming techniques to develop the model and voting techniques to help develop consensus in the determination of criteria, importances and therefore in decision solutions.

There are too many decision support software tools available on the market to discuss in detail here, but it is clear that the benefit that these tools bring to the decision making process in terms of time saving, problem visualisation and consensus building, is too significant to ignore.

6 Summary of the Review's Findings

This overview has identified the key principles of decision analysis methods. It has described the decision analysis process from the identification of the decision problem type (design or evaluation) through to the evaluation of alternatives and the selection of the best alternative according to the specified criteria and preferences of the decision maker. A wide range of the decision analysis methods available has been described and their limitations and strengths have been discussed.

It is clear from this review that many helpful methods exist that have the potential to support decisions within the management of structural assets. Based on this review, the following lists the recommended methods for use in decision making to support the management of structural assets.

6.1 Identify problem or opportunity

In the field of structural asset management, it may be someone other than the asset manager who notices that either something is amiss or that some likely decision opportunity exists. However it is clear that the asset manager must initiate a careful and deliberate inquiry into the problem to ensure a clear understanding of the basic need which the decision is to fulfil. This must be evaluated from many different viewpoints in addition to his own. The definition of the problem would be best evolved through a series of discussions with the other stakeholders until a clearly defined problem can be presented.

If the problem or opportunity to be solved is not clearly identified at this stage then confusion can occur later in the decision analysis process when further details are defined. These problems could be further magnified if more than one decision maker is involved in the process.

6.2 Identify Stakeholders in the decision

The possibility of more than one decision maker being considered, or of other stakeholders having an interest in and an influence over the decision process is a significant part of the decision making process. Even where the formal procedures of an organisation dictate that an individual has responsibility for making the decision, the views of interested parties will usually need to be sought. The overall objective of accounting for all appropriate decision makers and stakeholders in a decision making situation is to obtain ownership of the decision and commitment to its implementation from all affected parties.

The different methods of reaching group consensus in a decision making process can be broadly grouped into sharing, aggregating and comparing methods and involve negotiation, joint scoring systems and voting techniques. Each of these methods could be appropriate in different situations depending on the strength of feelings of different stakeholders and their relative power.

6.3 Identify viable alternatives

The whole purpose of decision analysis is to select the best alternative from the set of available alternatives. The real problem in decision making tends to stem from a failure to produce sufficient feasible alternatives. Therefore, it is necessary in any decision analysis problem to identify all of the alternatives available. This complete set can then be screened against rational criteria to bring the number of alternatives back to a manageable size.

Structural asset management decisions usually fall into the category of the evaluation problem, therefore only methods relating to this type of problem will be discussed here.

Of the techniques available for generating alternatives, the simpler methods such as attribute listing and brainstorming appear to be the most appropriate in these applications as they involve little methodology for a potentially high output. Also the availability of interactive software to support brainstorming, helps to make the process less tedious for the decision makers involved.

Any screening method that is then used to reduce the set of alternatives again should remove alternatives that are infeasible, unacceptable or dominated by other alternatives without removing very good alternatives.

6.4 Formulate decision objectives and criteria

The decision criteria are comprehensive and measurable representations of the decision maker's objectives used to describe the different alternatives.

If the alternatives are known, then a "bottom-up" approach can be adopted to determine the decision criteria. The alternatives can be compared to see how they differ, or to identify their strengths and weaknesses. These observations can then help formulate the set of important criteria on which the decision has to be made.

Once the decision criteria have been established, it is important to identify minimum standards on any of the criteria, which will act as constraints on any of the alternatives.

6.5 Structural Analysis

A decision matrix can model fairly straightforward decisions under uncertainty although in structural asset management it is unlikely that the decisions would be this straight forward.

An influence diagram, provides a simple graphical representation of a decision problem. It is particularly useful for the structuring phase of problem solving and for representing large or complex problems. The decision tree format, enables the sequential decisions to be represented and the consequences of future decisions to be traced back to assess their influence on the present decision. However, decision trees show more detail of the problem than influence diagrams and can, therefore, get messy and out of hand.

In addition, the structuring process can be the time in which the decision criteria are defined in more detail. The Analytic Hierarchy process helps the decision maker to arrange the criteria into some sort of hierarchy so that the lowest level criteria are measures for the criterion in the next level above.

6.6 Uncertainty and probabilistic analysis

The most detailed evaluation of uncertainties that is mentioned in the decision analysis literature is the risk assessment method originally described by Hertz. This method, from the quantitative risk assessment field of work, is a form of Monte Carlo Simulation. It rigorously accounts for uncertainty through the definition of subjective probabilities, but for that reason consumes a significant amount of computation time.

Structural reliability methods attempt to treat rationally, the various sources of uncertainties involved in a design or assessment process. The uncertain parameters are modelled using appropriate probability distribution functions and the probability of failure of the component is calculated. If the computed reliability is higher than the specified “target reliability”, the component is considered to be acceptable.

The results of the separate reliability analyses can be combined, if necessary, to calculate the overall reliability of the component.

The probability of failure can be calculated using numerical integration, Monte-Carlo simulation or FORM/SORM methods. Direct numerical integration is only feasible if the number of basic variables is less than about 5. Monte-Carlo method becomes computationally expensive if the failure probabilities are very small, which is typical of many structural components.. In a First Order Reliability Method (FORM) a linear approximation to the actual non-linear limit-state function is used, while in a Second Order Reliability Method (SORM), a quadratic approximation is used. These methods compute the failure probability very efficiently, and have become the most widely used methods in recent years

If such a detailed assessment is not required, or an initial view of the problem is required before detailed analysis, then a simplified risk scoring system can be used.

6.7 Utility/Value Analysis

Once the decision problem has been formulated, it is necessary to evaluate each alternative in the light of the decision criteria, so that the “best” alternative can be chosen. There are two types of preferences to be considered in the decision analysis. These two types of preferences: utility and weighting are inter-linked and the most practical techniques for modelling both of these types of preferences are the Simple Multi-Attribute Rating Technique and the Analytic Hierarchy Process. These methods use simple comparisons to produce importance ratios to represent individual or consensus preferences between criteria.

6.8 Selection of “best” alternative

There are several methods available for selecting the best alternative once the attributes have been scored and weighted. In the analytic hierarchy process, once the weighted scores for each attribute have been determined, they are summed for each alternative and the alternatives are then ranked according to their total weighted scores. The “best” option would be the one with the highest score.

Other methods are available, although they don’t take a direct sum of the score but look at the scores for each attribute individually. One of the most common methods that makes use of informal preferences is the Expected Value Principle, as this allows calculations of risk to be performed and communicated to decision makers in a straightforward manner.

6.9 Sensitivity Analysis

Sensitivity Analysis is an integral part of the decision modelling process. One purpose is to protect against a decision treating a symptom rather than the cause. Sensitivity analysis can also be carried out in the context of the problem structuring, this could result in requiring a more complete set of possible outcomes, or a more detailed description of the outcomes. The third way that sensitivity analysis can be of assistance is to determine which variables are important and therefore which uncertainties would be best refined. Finally sensitivity analysis can be carried out to determine the diversity of individual decision maker's preferences, the effect of those preferences on the consensus weightings and the sensitivity of the final outcome to any conflicts that may have arisen.

6.10 Final Remarks

It can be seen, that there are still significant opportunities for further work. At a detailed level, for example, the development of utility functions is still very complex if a detailed non linear relationship is required between utility and each criteria, although these can be created intuitively if necessary. The prediction of failure consequences is also very difficult as actual failures are very rare and so data is very limited. The evaluation of a distribution of the utility for each consequence of each alternative is a very complex process that is still to be finalised. Further research is also required to identify the best methods for carrying out sensitivity analysis. At a higher level in the framework, opportunities exist to develop interactions between the separate theories to produce an holistic decision analysis tool that can handle all of the complexities and conflicts involved in the management of structural assets..

These methods have been discussed in the context of decision problems from the field of Bridge Management. It is felt that due to the significant uncertainties involved in Bridge Management and the broad variety of strong opinions held by the different stakeholders, decision analysis can offer a rational and auditable method for combining all factors and opinions to arrive at the best decision for all parties. There is still work required to identify and apply the most appropriate decision tools to each stage of the decision process when considering risk based decisions for the management of structural assets. As part of this development, to enable a more generic but practical process to be developed, work is now commencing to apply these methods to the management of subsea pipelines

In summary, the principal aims of decision analysis, are to help decision makers:

- to explore the problem situation
- to learn about their own and other's values and judgements
- to identify a preferred course of action

This process when applied carefully, will lead to better considered, justifiable and explicable decisions.

7 Conclusions

In nearly every industry, many difficult and complex decisions are made concerning the industry's assets right throughout the asset's life cycle. At each stage of the life cycle, the type of decision, the number of alternatives available, the uncertainty in the information available and the number of people influencing the decision, all vary. However, one common factor within all these decisions is that they all involve risk.

The asset managers responsible for making these decisions are required to justify the basis on which the risks are managed. In some industries, such as bridge management and offshore, there is a requirement to show that codes and standards have been applied appropriately. In the cases where the codes and standards are met for at least one of the decision alternatives, the decision making is considerably simplified. Risk can be removed from the problem by removing all of the alternatives that did not meet the standards (assuming that minimising risk is the primary decision criteria). The decision between the remaining alternatives can then be based on a simpler range of factors such as cost and may involve a cost benefit analysis to account for environmental effects and even stakeholder values and company image. Although the risk based decision framework presented in this paper can be applied in these situations, it will often not be necessary, as direct comparison of the alternatives on a cost basis can be carried out. If however, further decision criteria need to be considered on a non cost basis, then some of the stages of the risk based decision framework could be very beneficial.

In the cases where the codes and standards do not apply or can not be adhered to, detailed engineering analysis and risk assessment has to be carried out to prove the safety of the structure under consideration. In these situations, the risk of failure becomes a much more significant part of the decision problem, and the decision alternatives become much more difficult to compare. In addition the consequences of failure become much more far reaching and so influence a wider range of stakeholders whose needs then have to be considered in the decision process. In addition to these complexities the additional decision factors such as environmental issues, political pressures, costs, company image, etc. all need to be accounted for. It is in these situations that the risk based decision framework, presented in this paper, is of most benefit.

The framework allows risks to be fully accounted for in a quantitative manner and for as many other decision factors as necessary to be accounted for. Each decision factor can be assessed in its most convenient for and therefore does not require for difficult judgements to be made to bring all factors to a common cost basis. In addition, if it is necessary to reduce the level of risk in any solution, it is possible, through sensitivity analysis, to identify the areas to which the decision is most sensitive and gather further information to reduce the uncertainty.

The greatest benefit of the risk based decision framework is the rational and auditable manner in which:

- The problem situation can be fully explored.
- Significant risks can be evaluated and quantified.
- A variety of opinions, values and judgements can be accounted for and combined.

- A preferred course of action can be identified and agreed upon through discussion and consensus building.

This process when applied carefully, will lead to better considered, justifiable and explicable decisions.

After this paper had been written a draft report was published by the UK Offshore Operators Association (UKOOA) [53]. The report outlines a framework to support decision-makers in identifying and evaluating the appropriate decision factors for a given situation and establishes the most appropriate basis for the decision depending on its context. The framework helps the decision-maker determine the extent to which good practice, risk analysis and stakeholder values should be considered in each situation depending on factors such as:

- The novelty of the decision situation.
- The extent of established practice to solve the problem.
- The interest and involvement of stakeholders.
- The significance of uncertainties in the decision.
- The severity of economic implications.

The report came to very similar conclusions to those outlined above. It described a type of decision problem that is novel and challenging; that involves strong stakeholder views; major economic implications and significant risk and uncertainty, even with the possibility of lowering safety standards. This type of decision should be addressed through a combination of engineering judgement, cost benefit analysis, quantitative risk assessment and an evaluation of company and societal values. The solution of such a complex decision becomes much easier to handle if the risk based decision framework defined in this paper is used for support.

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