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CAROLINE M ROBERTS

RISK-BASED DECISION-MAKING FOR THE MANAGEMENT OF STRUCTURAL ASSETS

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CAROLINE M ROBERTS

RISK-BASED DECISION-MAKING FOR THE MANAGEMENT OF STRUCTURAL ASSETS

Supervisors: J. E. Strutt
J. M. Ward

November 1999

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Engineering

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ABSTRACT

This thesis investigates the benefit of risk-based decision methods in engineering decisions. A thorough literature review identified the major issues and limitations in current methods. Consequently a more comprehensive model was developed to account for the complexities of real life decision-making. The enhancements introduced to the model include identifying and evaluating stakeholder influences, decision objectives, criteria and preferences between criteria and decision outcomes. Monitoring and controlling important parameters during implementation is also included to ensure objectives are met and risks controlled. Tools and techniques were identified to support decision-making within the new model. The research focuses on how available techniques can improve engineering decision-making.

The model was applied to four case studies analysing real life, "live" decision problems in bridge management and pipeline management. These confirmed the relevance and importance of the model enhancements. The practicality of the methods, their benefits and limitations were evaluated such that the proposed model was enhanced further. The enhanced model was shown to bring enhanced understanding to all four case studies and made the decisions more rational, thorough and auditable. The fifth case study reviewed how unsupported decisions are currently made within the sponsoring company. This involved a detailed desktop analysis of past projects and interviews with senior engineers and provided further evidence, which emphasised the value of using the decision model.

General guidelines were developed based on the case study experiences to help the decision-maker identify the level of analysis required for different types of decision problems. These were defined as applicability matrices. The benefit of using a third party facilitator in each of the case studies was identified in terms of the roles of leader, liaison, disseminator, spokesman and disturbance handler. The balance between these five roles through the stages of the decision process was found to be important to ensure the facilitator does not dominate the decision.

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LIST OF NOTATION

ALARP	As Low As Reasonably Practicable
APA	Andrew Palmer and Associates
CAPEX	CAPital EXpenditure
CRINE	Cost Reduction Initiative for the New Era
EPIC	Engineer Procure, Install and Commission
FEED	Front End Engineering Design
FMECA	Failure Modes and Effects Criticality Analysis
FORM/SORM	First Order/Second Order Reliability Methods
FPSO	Floating Production, Storage and Offloading Vessel
FSA	Flame Sprayed Aluminium
HAZIDS	Hazard Identification Studies
HAZOPS	Hazard and Operability Studies
HGV	Heavy Goods Vehicle
MAOP	Maximum Allowable Operating Pressure
MFL	Magnetic Flux Leakage
OPEX	OPerating EXpenditure
PSV	Public Service Vehicle
QRA	Quantitative Risk Analysis
SMYS	Specified Minimum Yield Stress
UKCS	UK Continental Shelf
UKOOA	UK Offshore Operators Association

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2 INTRODUCTION

A successful economy is reliant on well-maintained assets such as buildings, structures, plant and equipment. These assets have to be in a state to ensure the safety of personnel and the environment, efficient operation and adequate profit margins. Breakdowns or closures and low efficiency put pressure on profits and reduce the level of service supplied. In contrast to this, excessive maintenance time and costs also reduce efficiency and profits. Asset managers are therefore required to make difficult decisions at every stage of the asset's life, to achieve a proper balance between safety and profits, maintenance and productivity. These decisions include:

- Start-of-life decisions (such as the selection of materials and geometries and the acceptance of safety margins and design lives),
- Mid-life decisions (when to inspect/maintain and how to inspect/maintain),
- End-of-life decisions (such as life extension, rehabilitation or decommissioning).

In recent years, the press coverage of structural failures has increased and society has found a growing voice in environmental and safety issues. Environmental and civil rights pressure groups have become more vocal and more acceptable by the media. There is now less acceptance of the consequences of structural failure. The companies responsible have to be able to show a duty of care to the environment and the communities they affect. If the companies fail in this, the consequences to them in terms of damaged reputation and lost business as well the cost of lawsuits and compensation can be crippling.

Despite these increased complexities and significant consequences, individual asset managers are under increased pressure to make quick but confident decisions concerning the asset structural integrity. These managers also have less opportunity to seek support from seniors. In some companies, the age of "empowerment" has meant "passing the buck" to the more junior managers if the decision is perceived to be wrong.

This increased pressure combined with a lack of training has meant that many significant decisions are not evaluated properly in terms of addressing all options and accounting for all risks. Stakeholder issues are often ignored until it is too late and external pressure groups are perceived as an enemy rather than as a participant in the decision outcome. Key examples of poorly evaluated decisions include,

- the decision to start up a condensate pump while undergoing maintenance causing the Piper Alpha disaster [1],
- the initial decision to sink the Brent Spar platform west of Shetland causing public outrage [2],
- the decision to launch the space shuttle in exceptionally cold weather, despite the known o-ring problems, causing the Challenger disaster [3].

This research, while relevant to all branches of industry, focuses on two specific areas:

- transport infrastructure, specifically the management of road bridges;

- upstream oil and gas, specifically the design and management of subsea pipelines.

Both industries have a high profile in society, owning a huge number of assets involving design, installation, maintenance and decommissioning. Both of these industries are however constrained by tightly controlled budgets and affected by government policies of taxation, environmental issues and government spending.

2.1 Decisions in Bridge Management

UK government spending of the road transport budget is focussed more on maintaining and repairing existing bridges than on building new ones. This is a result of both lower public spending and recognising the significance of existing bridges in maintaining the integrity of the nation's infrastructure.

Bridges do not, and were not expected to, last forever, but if they are managed properly, they should achieve at least their design life of 120 years, and probably more. As part of the management process, existing bridges need regular maintenance and are subject to repair and rehabilitation when excessive deterioration or damage is discovered.

The management of DoT bridges falls into three distinct areas of work: steady state maintenance, assessment and strengthening of bridges not conforming to the DoT standards, and upgrading of sub-standard features.

The choice of strengthening method from a number of alternatives is currently decided based on minimum whole life costs accounting for the predicted cost of traffic delays during works. Comparisons are made of the estimated cost of different options that give the structure different estimated remaining lives.

A major limitation in current practice is in the regional decision-making process. The decisions made at these levels are dominated by subjective judgements. The inspection data available to the maintenance agents are crude and hence do not allow quantitative deterioration and capacity assessments to be made. The bridge condition and the deterioration criticality are also assessed subjectively. The uncertainty involved in loading, capacity and deterioration assessments results in the re-qualification of existing bridges being based on conservative, deterministic codes with large safety factors overcompensating for the uncertainties in these values.

The decisions to prioritise maintenance between bridges are dominated by a few key factors, such as the safety of the bridge, the overall repair costs or the need to minimise traffic disruption. All of these are established subjectively. In addition, the comparison of costs and benefits for different bridge maintenance projects is not consistently carried out. Trade-offs are required to select the "best" projects as different projects score better in terms of different issues. For example, one project may strengthen a bridge to a high level of safety while being very expensive, while another project may give only a small strength advantage but at very little cost.

2.2 Decisions in Pipeline Engineering

Until recently, the continuing low oil price has left no margin for profit, which has limited and continues to limit future investment. The need to continue to reduce costs

and increase competitiveness is paramount to the industry's survival, both in new developments and in maintaining and extending the life of older developments, to safeguard the thousands of jobs that rely on it.

In 1986 and 1992 the oil prices collapsed, bringing national and international activity to a grinding halt. In 1993 this problem was 'officially' recognised by the UK government following a report produced by a DTI working group investigating UKCS (UK Continental Shelf) oil industry competitiveness. A result of this investigation was the introduction of a Cost Reduction Initiative for the New Era (CRINE) proposed in June 1992. It was recognised that the problem of escalating capital and operating costs against continuing low oil prices was becoming prohibitive to the development of many marginal oil and gas discoveries. CAPEX (Capital expenditure) and OPEX (Operating expenditure) had to be reduced.

In the last two years it has become clear that the initial evaluation of cost reduction strategies is nearing its end. Cost reduction in isolation is beginning to acquire a bad name. Warnings have been made of the consequences of cost reductions on safety and on the industry's smaller companies. Instead, the concept of increasing competitiveness has emerged as the way ahead. Competitiveness addresses a wider gambit of issues including cost, quality, scheduling, customer relations and innovation.

The issue of safety in the industry and its associated cost has raised the question of "how safe is safe enough?" In general, the maximum allowable level of risk of fatality (individual risk) for the offshore industry has been accepted as being around 10^{-3} per year (1 fatality per 1000 person-years) for a given activity. A negligible level of risk is often taken to be about 10^{-5} or 10^{-6} per year (1 in a million years). Between these two limits the risks should be reduced if it is reasonably practicable to do so (ALARP). The ALARP principle involves a process of evaluating risks and reducing them where it is reasonably practicable. The test of "reasonable practicality" is based on cost-benefit analysis and introduces the concept of value for life. The decisions involved in such a process are therefore complex and significant.

A major limitation of current practice is in the decision-making process. The decisions are dominated by subjective judgements. Crude inspection data contains significant uncertainties making quantitative assessments of deterioration and capacity difficult.

Decisions to repair or replace pipelines are dominated by a few factors. These include the pipeline safety/integrity, the overall costs for repair or replacement and the need to minimise operational downtime. These factors are frequently established subjectively or they based on very uncertain data. In addition, the comparison of costs and benefits for different pipeline repair/replacement strategies is not evaluated consistently.

2.3 Research in Risk-based Decision Analysis

Risk-based decision analysis is a field of research that has been active for at least the last forty years in the fields of economics and operations research. It has developed a vast range of models, theories and processes that offer support to the decision-maker in terms of gaining insight into the decision problem. These methods allow the decision

problem to be decomposed into a set of smaller and easier to handle problems. Decision theory practitioners claim that the methods help the decision-maker to learn about their own and other's values and objectives concerning the problem. They also claim that it promotes creativity in the way the decision is made. Some of the theories also help identify and quantify uncertainties and risks. It is claimed that risk-based decision analysis helps decision-makers make better and more rational decisions.

Risk-based decision-making has been predominantly used in the fields of finance, commerce, government and medicine. Little use has been made of these methods in the field of engineering, especially in the management of engineering structures. However, due to the problems and complexities encountered in decision-making in this field, as described above, it is believed that these methods have the potential to transform the effectiveness and efficiency of its decision-making.

2.4 Research Objective

The objective of this research therefore, is to investigate if and how risk-based decision-making theories, developed outside engineering, can support engineering decisions. A generic process to support engineering risk-based decisions will be proposed based on current literature. This will then be applied to real life examples to investigate the benefits and problems that can arise from formalising such a process. The research focus will not be on the development of new techniques so much as investigating how the available techniques can improve decision-making in an engineering environment.

The overall objective of this research therefore, is to evaluate the benefit that risk-based decision-making can bring to real life engineering decision problems through:

1. Identifying tools and techniques that can be used to support decision-making;
2. Developing a more comprehensive model to address the major issues of decision-making, within which the various tools and techniques can be applied;
3. Applying the model and the appropriate tools and techniques to a range of real life decision problems;
4. Analysing the effects of using this model and drawing conclusions on how well it works and any implications for decision-makers.

3 PROBLEM DEFINITION

Decision analysis has predominantly been used in very limited fields such as finance, commerce, government and medicine. Minimal use of decision analysis methods has been made in the field of engineering, which is the specific area of consideration in this review. Engineering, by definition, is concerned with detailed analyses of machines and structures. The results of the analyses inform the decisions that are made. These decisions can involve product design, feasibility, production, maintenance, marketing or sales. The analysis is usually performed with extreme care and accuracy. The decisions can be based on subjective judgement and intuition, accounting for just one or two dominating criteria, combined with conservative assumptions on the uncertain variables. The potential for decision analysis to improve engineering decision-making is significant and could result in the more successful application of engineering solutions.

In nearly every industry, difficult and complex decisions are made concerning assets throughout the assets' life cycles. In this case an asset is defined as an investment which supports the business, either produced by the business for revenue (e.g. a car for a car manufacturer) or used by the business to support the acquisition of revenue (e.g. a car for a roadside rescue service). The life cycle stages of project appraisal, project implementation and operation of the asset [4] should be extended for decision-making to include decommissioning as the end of life phase. For all industries each of these phases involves a number of intermediate stages which each involve decision-making. Sometimes these decisions are quite simplistic but at other times they are highly complex, involving many alternatives, data uncertainty, conflicting decision objectives and different stakeholder viewpoints. In many industries this situation is magnified by high safety and environmental risks and the high investment required.

At each stage of the life cycle, the type of decision, the number of alternatives available, the information uncertainty and the number of stakeholder influences, vary. In later life decisions there are a limited number of alternatives (such as whether to repair or replace a structure), the decision consequences only interest a local stakeholder group, the costs are less than the initial capital investment and uncertainties can be effectively modelled due to the availability of historical data [4]. In contrast, decisions made earlier in the life cycle involve significant investments, many alternatives, extreme uncertainties and a lack of information [4]. These decisions also tend to be high profile, with significant management input and with many other stakeholder influences. A well-defined and evaluated decision at the conceptual stage could remove the need for a difficult decision later in the asset's life.

3.1 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 these are summarised in Table 1 below.

Life cycle stage	Decision characteristics	Example decisions	
		Transport Industry	Oil & Gas Industry
Project appraisal			
Project definition	High level, qualitative decision based on limited data and subjective judgements.	Identify the opportunity or need to transport traffic across an obstruction (e.g. river).	Identify the need or opportunity to produce oil and/or gas from a new field development.
Feasibility assessment	Simplified quantitative decision based on limited data, subjective judgements and predictions of capacity, turnover, whole life cost and profit.	Justify the feasibility of transporting traffic across an obstruction (road, river, railway).	Justify the feasibility of producing and transporting oil and/or gas from a new development.
Conceptual design	More detailed quantitative decision based on limited data to check the feasibility and the cost effectiveness of the selected concepts. Significantly influenced by uncertainties.	Identify conceptual options from a chain ferry to a six-lane river crossing. Consider issues such as crossing location, capacity, construction issues, etc.	Identify conceptual transportation options including a tanker or a subsea pipeline. Consider issues such as tie-in points, capacity, construction issues, etc.
Project implementation			
Detailed design	Very detailed quantitative decision based on engineering predictions of safety, based on analysis and testing. Some uncertainty remains, such as magnitudes of loads.	Design bridge for safety and whole life cost through selecting dimensions and materials suitable for safety and durability.	Design pipeline for safety and whole life cost through selecting dimensions and materials suitable for safety and durability.
Manufacture/ procurement	High level decisions based on stakeholder preference, e.g. for certain contractors/suppliers.	Select contractor/ supplier to construct and procure bridge components.	Select steel mill to manufacture pipe and contractor to procure components.
Installation	Strategic decisions affecting the timeliness and accuracy of construction. They are dominated by uncertainties in manufacture completion/ component delivery and environmental conditions.	Determine installation/ construction schedule. This affects the commission date, the whole life cost of the project.	Determine installation/ construction schedule. This affects the commission date, the whole life cost of the project.

Pre-operation testing/inspection	Detailed quantitative decisions affected by uncertainties in environmental conditions and the accuracy with which operational and test conditions can be monitored and controlled.	Determine schedule and procedure for pre-operation testing and inspection.	Determine schedule and procedure for pre-operation testing and inspection.
Operation of asset			
Operation	Regular quantitative decisions based on capacity demands and market forces. Affected by uncertainties the accuracy with which operational can be monitored / controlled.	Determine and control flow capacities.	Determine and control flow capacities.
Inspection, maintenance and repair	Regular quantitative or qualitative decisions based on assessment of deterioration and failure rates. Affected by uncertainties in inspection results and deterioration models.	Determine schedule and methods for inspection, maintenance and repair.	Determine schedule and methods for inspection, maintenance and repair.
Requalification/ life extension	Quantitative decision based on uncertainties in historical and inspection data, and uncertainties/ vagueness in the future design requirements.	Reassessment of design initiated by changes in operational parameters, excessive deterioration, unexpected damage, or a need to extend the structure's life.	Reassessment of design initiated by changes in operational parameters, excessive deterioration, unexpected damage or a need to extend the structure's life.
End of life			
Decommissioning	Strategic decision based on uncertainties in the current condition, environmental conditions and future requirements have to be accounted for.	Decision to take the structure out of operation to a safe state when it is no longer required for operations.	Decision to take the structure out of operation to a safe state when it is no longer required for operations

Table 1: Identification of decision characteristics at stages in the life cycle

3.2 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 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 involved in risk-based decision-making for structural asset management as blocks and the relationships between them as lines linking the blocks [5].

This work had two purposes. Firstly, as a basis for structuring a decision process, it provides a model for all of the information that is required. Secondly, it is a checklist for all necessary research areas to complete the decision process.

The entity model was formulated from the research aim to "*develop a decision support process for managing the risk of a structural asset, to minimise the probability and consequences of "failure" as perceived by the stakeholders*".

The key entities and relationships were then mapped on to the entity model in Figure 1.

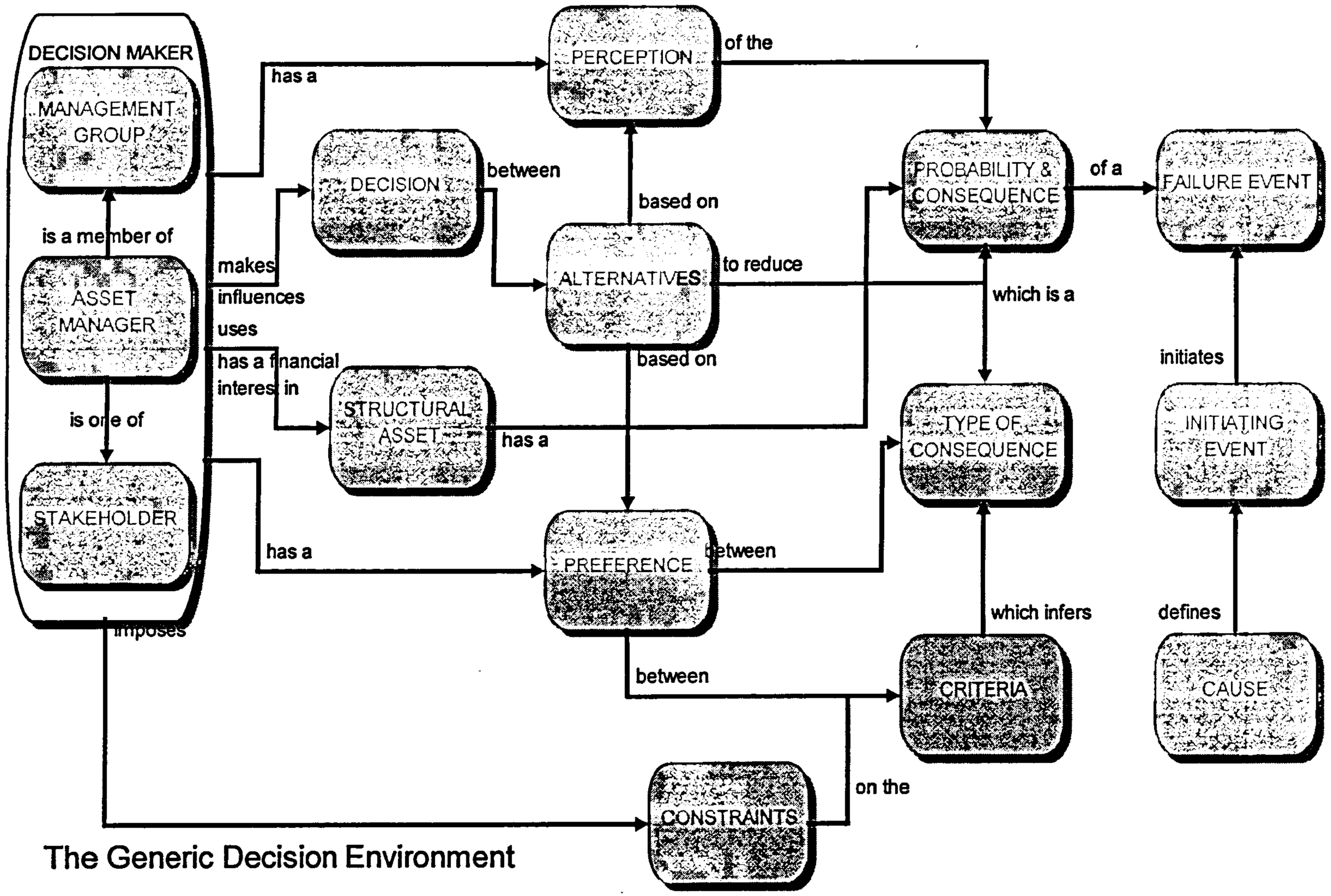
To help describe the generic decision problem and its solution an example decision problem has been adopted to illustrate each of the important points. The example decision was taken from the field of bridge management and considers the need to restrict, maintain or repair an under-strength bridge. The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

3.3 The Decision

The focal points of the entity model are the decision and the structural asset. But all parties must agree on what structural asset is being considered, what decision is to be made, how it can be made and under what constraints. The decision is then dependent on identifying all available alternatives and evaluating which is best.

In this example, the decision is whether a bridge failing assessment should be repaired, strengthened, or left as it is for another year. There are a number of different repair and strengthening options available and new techniques may still be identified. The decision is constrained predominantly by budgets and safety.

Risk-based Decision-making For The Management Of Structural Assets



The Generic Decision Environment

Figure 1

3.3.1 The decision-making group

The Decision-making group consists of the Asset manager, the asset management group and other stakeholders, all of whom are interested in and influence the decision, to different extents. It is necessary 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 those affected by the availability and/or safety of the structural asset. In this example, they would include bridge users (private, commercial and industrial), environmental pressure groups (campaigning for pedestrianisation, etc.) or government officials (MPs from local constituencies, etc.).

It is important to determine who the different stakeholders are, how they can be identified, what roles they play in the decision process and how to accounted for them.

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

The asset manager is responsible for the day-to-day asset operation including defining maintenance and repair schedules and bidding for funding. In this example, this would be the county or borough bridge engineer and could belong to the asset management group. It is necessary to identify the asset manager and his power in the decision.

3.3.2 The perceptions of the decision makers

Each decision-maker has different perceptions of the key decision issues, of which are important and the severity of the risks. These perceptions have to be identified and accounted for in the decision process. In this example, some stakeholders may consider that the safety of bridge users is of utmost importance. For others, keeping the bridge open for use by buses or lorries may be more important. Each decision-maker will also have different preferences over the decision criteria, the types of consequences and the probabilities of the consequences (risk prone or risk averse). These preferences need to be identified, measured and modelled.

3.3.3 Assessment of the risks

One of the decision objectives is to minimise the risk of structural failure. There are a number of definitions of risk currently in use by different groups of risk practitioners. These were summarised in a report by the Royal Society [6] as:

- Probability of undesired consequences.
- Seriousness of (maximum) possible undesired consequences.
- Multi-attribute weighted sum of components of possible undesired consequences.
- Probability multiplied by seriousness of undesired consequences (expected loss).
- Probability weighted sum of all undesired consequences (average expected loss).
- Fitted function through a graph relating probability to undesired consequences.

- Semi variance of possible undesired consequences about their average.
- Variance of all possible consequences about mean expected consequences.
- Weighted combination of probability distribution parameters for all consequences.
- Weight of possible undesired consequences relative to those that are desired.

Each definition seems logical in its own right, yet each is different. Some are more complex than others. In line with standard engineering risk assessment practice, the fourth definition has been adopted here:

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

The complexities of consequence uncertainty and multiple attributes will be introduced later in the decision analysis.

The risks considered result from different possible failure events. It is necessary for the decision process to clarify the failure events being considered. 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 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.

4 LITERATURE REVIEW

4.1 Introduction

For centuries, a philosophical debate has considered the hypothesis that human behaviour is, as a rule, rational. If rationality is defined as the ability to remain emotionally unaffected, or to understand and base decisions on personal motivations, then with effort, man can be rational. If rationality is the ability to equally consider all options and select the optimal one, then man struggles with this unaided.

Many decisions are complex. Decisions may involve multiple, conflicting objectives, where a better outcome in one objective results in a worse outcome in another. Decisions may involve a degree of uncertainty, where an uncertain outcome relies on an uncertain future event occurring. Some decisions may be sequential, 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, with different authority and influence levels, may have different decision objectives and preferences.

It is in the face of such complexity that man struggles to be rational and decision theory brings support. 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 [7]. Decision analysis decomposes the decision problem into a set of smaller and easier to handle problems. After each sub-problem has been dealt with separately, decision theory supports the integration of results to enable the selection of a course of action [8]. 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 to identify appropriate methods that could be used to support risk-based decisions required in the management of structural assets. These could include pipelines, bridges, power plants buildings and other capital equipment used for profit making purposes within industry. A high level review is therefore made of the methods adopted in other industries to support risk-based decisions. These include military, aerospace, power plants, bridges, offshore structures and pipelines. The key principles of the decision methods adopted in these fields are identified. This overview also briefly describes the history of the development of decision analysis, identifies key decision analysis principles and describes the decision analysis process and the types of methods available. The limitations and strengths of each method are discussed in the context of structural asset management. The review starts by considering what is meant by the term rationality and the influences that affect it.

Decision analysis is a very broad subject. The full scope of decision analysis encompasses a wide range of diverse subjects and theories including soft systems methodologies, the theory of constraints and neural networks. It is not possible to tackle such a wide range of subjects within this thesis. Consequently, this review is concerned with a subset of decisions where a finite number of alternative courses of action and outcomes are considered. This form of decision analysis is often referred to as "Classical Decision Theory".

4.2- Rationality in Decision-making

The aim of decision theory is to help the decision-maker to make rational decisions. However, what is a rational decision? Traditionally, the study of decision-making has tended to be normative, identifying what the decision-maker ought to do. This assumes that the decision-maker naturally behaves in a rational and logical manner. Consequently, the decision-maker is expected to maximise satisfaction by selecting the decision alternative with the greatest value. Research into descriptive decision analysis reveals that this is not the case in reality.

Decisions may appear to be irrational or sub-optimal due to lack of training or understanding on the part of the decision-makers. The nature of the decisions may make the assumption of rationality inappropriate. For example, a decision-maker would only be able to identify the best overall decision alternative if he had first identified all possible alternatives and all possible consequences. This situation is known as the condition of perfect knowledge [85].

In addition, the decision-maker would require a rational mechanism to consistently rank the value of each outcome to reflect his preferences. This situation is known as the condition of perfect judgement [85]. It reality these situations do not occur as decision-makers may only have limited knowledge, time and even ability to tackle many decisions. A distinction has to be made between perfect and limited rationality [9]. Furthermore, personal and organisational objectives are often derived from stakeholders' consensus, which may not equally account for all members' views, which in turn may be incompatible with each other.

In reality, the decision process is more likely to be based on minimum acceptable requirements rather than maximising payoff. This is known as satisficing behaviour [85]. Decision-makers however, would often prefer to maximise than to satisfy. They hold rationality, perfect judgement and knowledge as highly desirable goals. These goals are idealistic, but should still be aimed for. In order to improve the quality of decision-making it is necessary to investigate the sociological factors that make a simplified model of reality necessary. Some of the factors that limit the decision-maker's ability to behave in a rational, maximising manner are discussed below.

4.2.1 Perception

Perception is the process by which the individual receives, organises and processes data. From experience, we know that we do not take in and process all available information in a given situation. This is known as selective perception [85]. Evidence suggests that

individual perceptions differ based on personal needs, background and experiences [10]. Selective perception limits the information derived from a particular situation but which still forms the basis of future actions. We naturally try to organise the limited information in such a way that it seems to provide a complete picture, or a satisfactory explanation of the situation. This process is known as closure [11].

A common method of closure is to categorise decision situations according to past experiences [85]. Experience is a valuable factor in decision-making; however, it also has significant potential dangers since assumptions of familiarity can be misguided and incorrect. Stereotyping is another common form of closure, where an individual or situation can be evaluated based on one particular characteristic (e.g., sex, race, occupation) and all other cues are ignored in preference to personal beliefs. Finally, we can force closure in a situation by seeing what we expect to see. We can be preconditioned to organise perceptions into expected patterns through either forewarning or familiarity. Such expectancy can also be brought about by our own needs and enthusiasm for a particular outcome.

4.2.2 Values

Values are very significant in determining human behaviour. Individuals, groups and organisations construct and maintain value systems and use them to evaluate alternative courses of action. Individuals learn to adopt particular beliefs from organising and interpreting information [12]. Many beliefs are descriptive, where no judgement is implied. Other beliefs may be evaluative, where judgement is clearly implied. Some beliefs go even further and become prescriptive. Evaluative and prescriptive judgements involve assessing value and therefore affect the individual's decision behaviour [85]. When a number of compatible, related beliefs are organised into a stable pattern, an attitude is formed. Attitudes tend to pre-dispose us to behave in a predictable way. At a more basic level, general preferences (values) underlie attitudes, which are even more ingrained and significantly affect behaviour [13].

Values play an important role in decision-making behaviour [85]:

1. Most people are unaware of the values they exhibit in their behaviour, which can operate at a subconscious level.
2. Values affect judgements between alternatives, which are made in terms of perceived worth.
3. People pick out characteristics in others or in situations to support their personal value system, disregarding whatever does not fit.
4. Individuals are rarely entirely consistent in applying values to situations. Different values can be triggered by different stimuli.

4.2.3 Uncertainty

Decision-making, especially in the context of risk, involves assessing the value of outcomes and the likelihood of the outcome occurring.

Probability of an event is defined as the likelihood of its occurrence. It can be assessed objectively or subjectively. Objective probability must be based on an unbiased assessment of either historical data or substantial experimentation. Subjective probability is an expression of the degree of belief of an occurrence. This however has limitations [14]:

1. People tend to overestimate low probability events and underestimate high probability events.
2. People tend to predict that an event that has not occurred for a while is more likely to occur in the near future ("gamblers fallacy").
3. People tend to overestimate the probability of favourable events and underestimate the probability of unfavourable events.

The third point has an important effect on decision behaviour as it reveals a link between the value of an outcome and the assumed probability of occurrence. The theory of utility (which is described in more detail later in Section 4.5.3) considers the way the value of an outcome changes with decision-maker and with time and therefore affects the perceived riskiness of a gamble. The decision-maker can combine an assessment of the utility of an outcome with the likelihood of the outcome to give a subjective expected utility, which can be used as the basis of decision-making under uncertainty. This can also be applied to the risk itself so that low risk outcomes can be made more or less attractive than high-risk outcomes. The tendency for decision-makers to accept a higher or lower risk more readily is known as risk propensity. This has a significant effect on a decision-maker's approach to decision-making. These issues are also discussed in more detail in Section 4.5.3.

4.2.4 Limited rationality

It has been shown that most decisions are not perfectly rational. However, after taking account of all influencing factors decisions can be made under limited rationality. By simplifying rational decision-making to the assumptions of limited rationality, a rational decision can be defined according to Lee's [15] four characteristic principles:

1 A rational decision is one from a specified set of possible decisions. If all possible options are not identified, then the best decision will only be the best of those identified and could therefore be sub-optimal.

2 A rational decision depends on the decision rule employed by the decision-maker to specify which of the set of possible decisions is rational.

3 The rational decision for a specific situation may differ between decision-makers, because people's subjective probabilities and consequence values differ.

4 A rational decision depends on the information available. It is judged irrational to ignore relevant available information. Large quantities of information could, however, take excessive time to assimilate. The decision-maker has to evaluate the time, effort and costs required to obtain adequate information for a rational decision.

4.3 A Review of the Risk-based Decision Process

The first seeds of decision theory seem to have been sown early this century in two different fields. In the field of economics, Alfred Marshall [16] 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 expected to bring him maximum gain. In the field of mathematics, Ramsey [17] was the first to express an operational theory of action based on both judgmental probability and utility involving a subjective or decision-theoretic viewpoint. Von Neumann and Morgernstern [18] then developed the modern probabilistic utility theory in 1947. Utility theory first had been conceived in the 17th and 18th centuries but was dropped in the mid 19th century as an immeasurable science. Von Neumann and Morgernstern revitalised utility theory and pointed the way to scientific methods to measure conflicting criteria and thus devised a set of axioms for preferences between gambles. Mosteller and Nogee [19] set out to test the descriptive adequacy of Von Neumann - Morgenstern theory by measuring the utility for small amounts of money for real people. An example of the typical utility functions they found is shown in Figure 2. Each line represents an individual participant, groups A and B were undergraduate students, group C were national guardsmen. The students were found to behave far more in accordance with classical diminishing returns notions than the guardsmen, this was thought to be due to the less favoured economic status of the guardsmen.

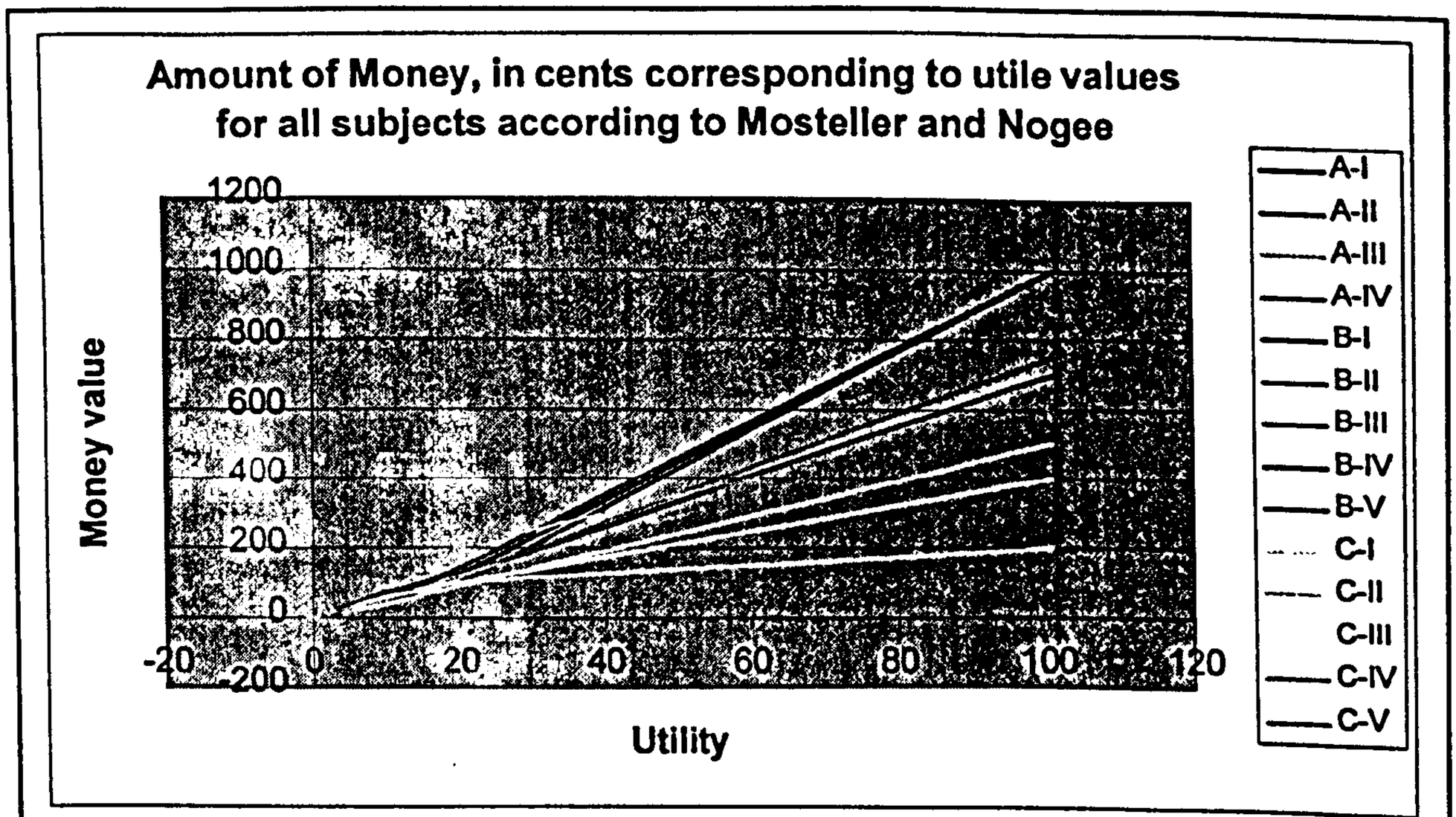


Figure 2 Typical utility curve based on experiments by Mosteller and Nogee [19]

Mosteller and Nogee's technique, however, was criticised, as people do not, as they assumed, base decision-making on objective probabilities. Davidson, Suppes and Siegel [20] followed up Ramsey's [17] methods for subjective probability and utility

free of this criticism. The utility functions they found for money, (shown in Figure 3), also reflected the utility curve hypothesised by Friedman and Savage [21] with a similar falling off in marginal utility. A pair of curves represent the upper and lowers bounds for each participant between which the true utility curve would lie.

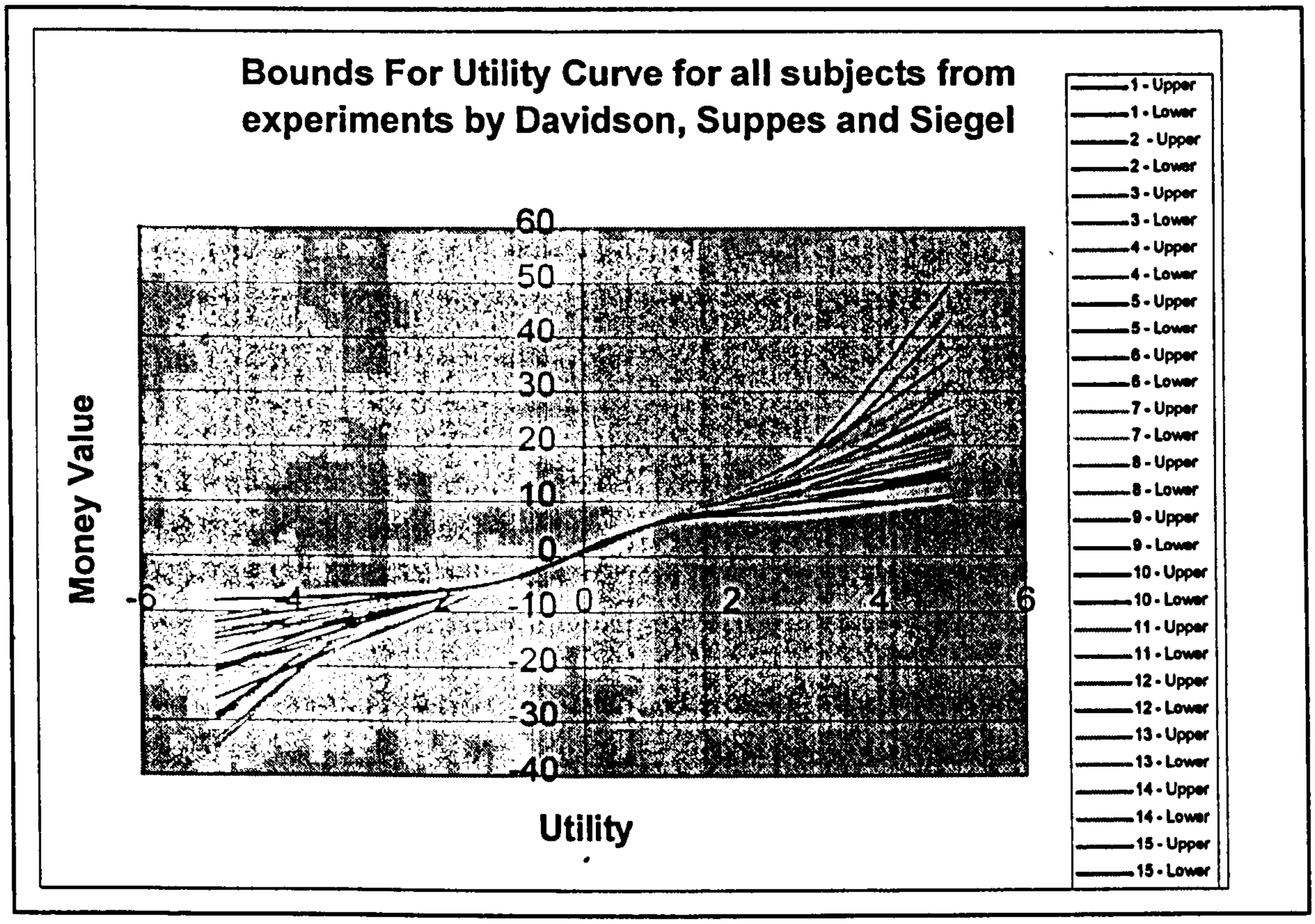


Figure 3 Typical utility curve from Davidson, Suppes and Siegel's experiments [20]

Decision theory was first developed by mathematicians and economists, behavioural decision theory then came about as a result of psychology. Behavioural decision theory is concerned with the hypothesis of general rationality and aims to explain human decisions. Normative decision theory concerns choices that a rational man should make in a given situation regardless of the decisions actually made. 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. Likewise, mathematicians have usually been more concerned with the mathematical theory of rational decision-making and the development of the mathematics of optimisation.

A key source for modern decision theory is Raiffa [22] who defined the decision analysis process as:

1. List viable options available for gathering information, experimentation and action.
2. List the events that may possibly occur.
3. Arrange the information required and the choices to make in chronological order.
4. Decide preferences for the consequences resulting from the various actions.

5. Judge what the chances are that any particular uncertain event will occur.

Keeney and Raiffa [23] proposed a more thorough and logical decision-making process as:

1. Pre-analysis - This involves identifying the problem and the viable action alternatives available.
2. Structural Analysis - This involves identifying which choices can be made now and which can be deferred. It also identifies the necessary information or experiments to inform the choices. The decision-maker can order and address these questions through a decision tree.
3. Uncertainty Analysis - The decision-maker assigns probabilities to the branches on the decision tree. These can be 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 the decision tree paths. The consequence of each path fully describes the implications of that path. The decision-maker then encodes his preference for the consequences in terms of a utility number such that the maximisation of expected utility becomes the decision basis.
5. Optimisation Analysis - The decision strategy optimises expected utility. This strategy indicates what the best action at the start of the decision tree and at every decision node along the decision tree.

This process is a good starting point for decision support but it has limitations. Firstly, the process is based on a single decision-maker, not accounting for group dynamics or conflicting stakeholder views. In reality, more people may be involved in the decision, with their own perceptions of the risks and preferences for final outcomes. Secondly, the process assumes that the decision-maker starts the analysis completely undecided and that the decision process reveals a set of answers to be scrutinised to ensure consistency. However, the decision-maker may already have preconceptions, 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. The process also 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.

Many decisions involve multiple conflicting objectives, poorly quantified uncertainties, costs and benefits relating to individuals and organisations, long-term consequences and societal impacts. Keeney and Raiffa's decision process does not aim to generate an "objectively correct" answer to the problem based on this array of complexities. Such a response could be impossible and if possible is likely to be irrelevant. Instead, this

process is able to receive subjective evaluations for unquantifiable criteria, along with objective values for quantifiable criteria.

Keeney and Raiffa's decision process was aimed at supporting both strategic decisions (e.g. how much to invest in a certain field of research) and repetitive operational decisions (e.g. how much to charge for a certain product). The strategic decisions are more complex to evaluate, but that is even more reason for decision analysis to be used to support it.

Finally, Keeney and Raiffa's decision process does not mention implementation of the solution or post analysis of the decision results. This stage in the decision process should identify how to communicate the right instructions to the right people, and who should be responsible for their completion. This should also include an evaluation of the results, both short term, (e.g. an immediate assessment of the fulfilment of objectives and a need to refine the evaluation process) and long term (e.g. monitoring the long-term decision results). This can result in the need to iterate the solution based on sensitivity, to ensure that no new variables or alternatives arise and that the final solution can be implemented.

Comparing Keeney and Raiffa's decision process with the generic formulation of the decision problem identifies whether the decision process does actually address all the entities (or issues) raised by the entity model. Table 2 below relates the entities to different stages in the decision process and identifies any gaps in the 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			✓		

Table 2: Relationship between the entities to the decision process

Based on this assessment of Keeney and Raiffa's proposals, we can see that a number of gaps exist in their proposed decision process. These gaps are:

- The need to identify and account for multiple decision makers (or stakeholders);
- The need to identify decision criteria (especially if multiple criteria are needed);
- The need to identify constraints on the decision;
- The need to review the whole decision process to identify opportunities to improve the evaluation. This could be achieved through sensitivity analysis and model refinement at the end of the decision process [24].

I have concluded that it is therefore necessary to develop an enhanced decision process that will provide for the deficiencies identified in Keeney and Raiffa's process. This will also provide a much richer basis for evaluating decision problems. This enhanced decision process is shown in Figure 4. The boxes representing decision steps originally proposed by Keeney and Raiffa are white, while I propose to introduce the shaded boxes as part of this research.

This enhanced decision process is the backbone of this research. The enhancements ensure that all the inputs identified by the entity diagram in Figure 1 can be provided and hence ensure that all aspects of the decision problem are accounted for. This enhanced decision process will be used as a basis for a literature review into the available generic decision theories developed in the decision sciences. Based on the results of this review, the enhanced process will then be tested, with appropriate tools, on real life decision problems. First, to understand the current status of risk-based decision-making in engineering applications, a review is carried out of the application of the methods in various industries.

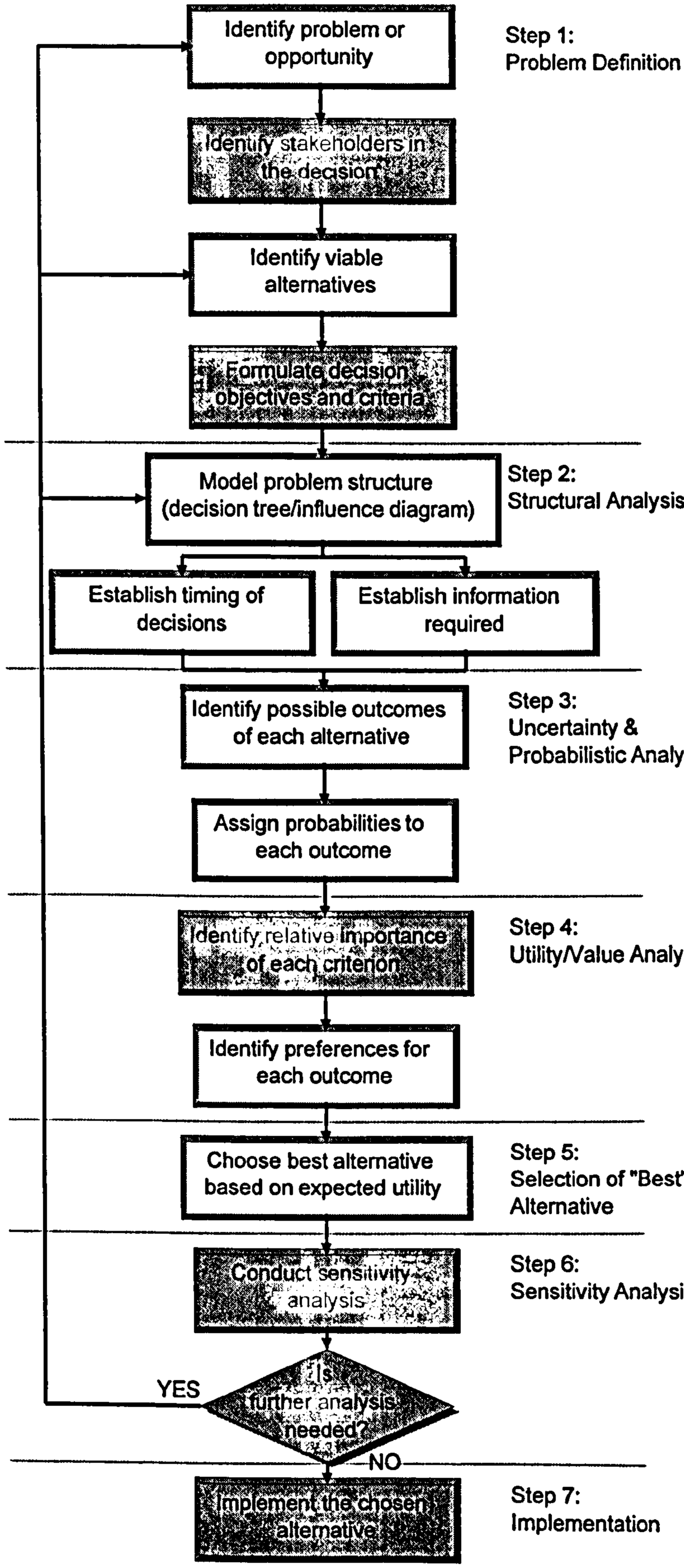


Figure 4: Outline of the proposed risk-based decision process

4.4 A Review of Applications of Decision Methods in Industry

A number of industries have applied and been responsible for further developing different forms of decision theory to support decision-making particular to those fields. A review has therefore been carried out of these decision theory applications in different industries, to identify any methods or experiences that would be of benefit to this research. The industries that have been considered are the military, aviation, plant management, bridges, offshore structures and pipelines.

4.4.1 Decision-making In The Military

One of the first application areas of decision theory was in the military. The focus here was in the application and development of game theory. Game theory is a mathematical approach to decision-making in conflict. It is applied to problems involving competition [101, 25]. Game theory addresses problems where two or sometimes more groups, have a number of options from which to choose, and the outcome depends on the decisions of all opponents with different aims. Important characteristics of game theory are the number of participants and options, the level of competition, the availability of information, the value of possible outcomes and the timing of the decisions.

The simplest form of decision problem is the finite two person zero sum game, where there are two sides opposing one another, and the gain to one is the loss to the other. Each side can choose from a finite number of strategies. The game is solved by constructing a "payoff matrix" representing the loss and gain for each side for each available strategy. Each side then tries to maximise their payoff.

The game is solved when the expected amount that one side will win if both sides use their best strategies, is determined. This is the value of the game. Each side then chooses the strategy giving them the expected gain/loss equal to the value of the game. Although the methodology for the solution of games exists if the game can be put into a matrix, the practical applications for the technique have proved to be limited. Game Theory has rarely been used as a tool for military decision-making. Its main use has been in the analysis of decisions after they have been made, either in real conflicts or during gaming. In other words, it is probably more suitable as a descriptive tool than as a direct decision-making aid. This is because in military conflict the games are often not zero-sum, nor is it likely that the opponents' scales of values will be common. It is also unlikely that one side will know the other's true preferences and the number of plausible strategies can be very large. This gives rise to large, unmanageable matrices.

Game theory could have the potential to support decision-making in situations of high stakeholder conflict, where the different stakeholders would be treated as opponents in a game model. However, the limitations described previously would also restrict the suitability of using game theory to help support these types of decisions. These limitations have been partially addressed in the Hypergame and Metagame extensions of game theory. These extensions of traditional game theory are able to handle more realistic problems [93, 94, 95]. The Hypergame approach recognises that the players

may have different perceptions of the game being played. These differences arise from their views of the outcomes, their perception of opponents' motives, their attribution of responsibility, their view of the options open to their opponents and even who their opponents are. The Hypergames are analysed by developing separate payoff matrices for each player and finding the "equilibrium" strategy where no player can improve on his own terms by unilateral change. The Metagame approach concentrates on the decision options open to the various "sides" in a problem. It is less formal than either classical game theory or Hypergames. Its most characteristic feature is its emphasis on the tactical, political and psychological relationships between the various "sides". Metagames are analysed by considering a number of scenarios or by analysing the threats and promises for each side within a strategic map. The formulation of both of these models is very complex and therefore has rarely been adopted.

Haywood wrote one of the first documented applications of Game Theory to Military decision-making in 1954 [26]. He applied the principles of Game Theory to the reconstruction of the strategic decision problem facing the two opposing commanders at the battle of Avranches in August 1944. This paper became a pioneering basis for the methodology of military analysis, particularly in the role of game theory in military strategic decision-making. However, more than 30 years after its publication previously secret military information concerning the battle was disclosed. This shed new light on Haywood's conclusions and raised questions over game theory's effectiveness as a military decision-making tool over the past fifty years [27]. Haywood claimed that the decision problem facing the US Commander against the German Commander could be modelled and assessed by using Game Theory. It was claimed that such analysis would show that the US Commander, considering all risks and options available to his opponent, had selected the best strategy available. However, an order direct from Hitler had stopped the German Commander following his best strategy. If the German Commander had selected his best strategy then the US victory may not have been so conclusive. The recent disclosure revealed that US military intelligence intercepted Hitler's order and therefore knew the German Commander's strategy before it was initiated. This allowed the US Commander to base his decision on certainty not uncertainty, removing the benefit claimed from Game Theory.

Another decision tool developed in this field is Military Appreciation [28]. Every military officer is taught Military Appreciation as a qualitative approach to decision-making. The approach aims to help senior officers be confident that all factors have been thought through in situations of extreme stress. The Military Appreciation is a disciplined process to support the examination of all relevant factors and produce a confidently reasoned conclusion. An appreciation is most useful as a written document for presentation to higher authority, but it can be used as a checklist, if time is short. A Military Appreciation is carried out in 7 main steps:

- Study the existing situation
- Specify the aim to be attained
- Examine and draw reasoned conclusions on all relevant factors

- Consider all practicable courses of action
- Decide on the best course of action to attain the aim
- Make a plan to implement the selected course of action
- Check all reasoning and the practicality of the plan

The appreciation is not an easy method to apply and it is important not to let the form become the substance. However, it is a useful and effective method for supporting decision-making in those cases where mathematical techniques are inappropriate. This type of checklist provides a helpful starting point for developing a decision framework for both quantitative and qualitative decision-making in any field of application.

The Mission Orientated Approach (MOA) [29], is a decision technique that develops a hierarchy to connect the individual requirements to the overall mission. The hierarchy creates a ladder by which the effects of equipment at tactical level can be combined to show the resulting ability to satisfy the strategic direction. The hierarchy starts at the strategic level, which describes the degree to which the overall mission is accomplished under different scenarios. The next level acknowledges both that the strategic level is too broad for practical planning and the necessity to identify the essential elements of the overall mission. These are the Key Mission Components (KMCs). They correspond to major aspects of military operations, failure in any one of which would jeopardise the overall strategic mission. KMCs are supported by a series of military functions, which represent the level in the military world at which equipment is issued and used.

MOA is a structured judgement approach, where different types of judgement come from different sources. The technical assessments of capability are provided by technical experts and the judgements relating functions to KMCs and the KMCs to strategic capability are provided by more senior officers. MOA therefore ties together disparate sources of information and judgement that could make it difficult for any one person to influence the decision too much. This makes the best of the available information. This type of structuring technique is very similar to Saaty's analytical hierarchy process [100] in that it is useful for breaking the decision into manageable levels and identifying influencing factors at each level.

It is concluded that the decision-making methods adopted in the military are therefore designed to account for qualitative rather than quantitative data, and account for significant uncertainty and conflict in stakeholder/opponent views.

4.4.2 Decision-making In Aviation

Another important field for using risk-based decision methods is aviation. This field addresses two problems: design optimisation and inspection/maintenance scheduling.

Design optimisation involves a trade-off in reducing weight against maximising safety. One method developed to address this problem uses Genetic Algorithms [30, 31]. These are parameter search procedures based on the mechanics of natural genetics. They combine Darwinian "survival of the fittest" to eliminate unfit characteristics with

a random yet structured information exchange exploiting knowledge from old solutions. This technique has become popular in recent years as a robust optimisation tool for a variety of problems in engineering, science, economics, finance, etc. A number of structural design applications have been documented, for example in [32, 30], to maximise strength to weight ratios.

Another example of design optimisation considered the trade-off of cost and risk (although this was a simplified version of the real problem, which involved risk reduction, cost, technical feasibility, weight and performance). The example assessment was performed conceptually [33] to illustrate a proposed method for finding the most cost effective of a number of risk reduction strategies in the presence of uncertainty. The uncertainties in the decision attributes were expressed as probability distributions based on engineering analyses. The decision-maker then compared the usefulness of each option against his objectives. To avoid the problems associated with the evaluation of multiple attribute utility each option was assessed separately against each attribute (i.e. risk and cost). Further evaluation was then required to separate the strategies, through benefit-to-cost ratio and expected cost impact. Analysing the decision using a variety of indicators and presenting the results in a number of formats offered different perspectives on the problem. However, decisions considered on more than risk and cost, could become unmanageable and reveal unreconciled conflicts.

A Multi Attribute decision methodology was proposed by Hauge and Wright [99] showing how to identify the best overall strategy through reconciliation and involved six main steps:

- Initiation - involving identifying objectives, assessing their relative importance, determining risk acceptance criteria and identifying hidden objectives.
- Hazard analysis - involving identifying the hazards threatening the objectives and generic scenarios containing these hazards and assessing each scenario's criticality.
- Risk assessment - involving collecting relevant data, verifying the criticality of each risk scenario, classifying them into risk categories, and then calculating the overall risk.
- Countermeasure analysis - involving identifying all possible countermeasures to each risk scenario, evaluating their costs and effects and calculating their utility if other indirect factors need to be accounted for, then carrying out a sensitivity analysis.
- Countermeasure deployment – involving both implementing and monitoring of the selected countermeasure's effectiveness.
- Post-implementation evaluation – involving evaluating the effectiveness and feeding back into the decision process any lessons learnt to support later decisions.

This process is very similar to that proposed by Keeney and Raiffa [23] and can also be used as the starting point for a decision framework.

Hauge and Wright went on to discuss the problems associated with trying to make such decisions based on both qualitative and quantitative uncertain information. The paper proposed the adoption of the Fuzzy-Bayesian extension to the Analytical Hierarchy Process [100] developed under the CEC funded project - RESTRUCT [34]. This method allows pair-wise comparisons of the relative importance of any two consequences, based on a set of descriptive terms. These are then translated as numerical values into a matrix, the principal eigenvalue of which gives importance weights for each decision objective. The countermeasures are then scored and ranked according to their weighted desirability against the decision objectives. The Fuzzy-Bayesian extension to this method allows the pair-wise comparison and the desirability scoring of each countermeasure to be performed using both fuzzy numbers and probability distributions. This allows different objectives to be integrated into a single desirability measure expressed as deterministic, fuzzy and probabilistic quantities. This approach was claimed to provide a systematic, flexible, intuitive and guided process, which does not remove any decision from management. It also supports the consideration of important but occasionally less conspicuous hazards, which may be overlooked in project management decisions.

Inspection and maintenance planning are extremely important activities in the aviation industry. For airline companies, maintenance costs can account for 20-30% of annual expenditure. However, maintenance planning can frequently be given second place to operational planning. The problem, therefore, is determining the extent of the maintenance and supporting the flight operations manager who has to face delayed and cancelled flights, unforeseen breakdowns, additional acute maintenance needs, etc. Rapid decisions are often required concerning delaying or cancelling flights, swapping aircraft and any maintenance implications of the decision. Reference [35] describes an interactive decision support system developed for the flight operations manager. The system supports decisions aimed at optimising service while still paying attention to maintenance costs. A heuristic approach was defined based on a cost coefficient computed from the aircraft's remaining flying hours, provided the maintenance is performed at the aircraft's latest overnight stay in a maintenance base before it runs out of flying hours. If the problem is discovered to have no feasible solution then maintenance slots can be interchanged. Such an interactive procedure allows the many additional factors to be taken into account.

The use of optimisation and operations research in the aviation industry is not new. Such maintenance scheduling problems have been the subject of considerable research over the last 10-15 years. However, only a few methods of "real" optimisation have been developed. These methods tend to be automatic with very little input from the decision-maker. Examples are the programmes developed by American Airlines [36] and Swissair [37] to control the execution of maintenance plans. The aircraft maintenance status was taken as the main input to the problem. Based on the average flying hours per day and the maximum flying hours between maintenance, the latest date at which each aircraft should go in for maintenance was determined.

The decision-making methods adopted in the aviation industry are therefore designed to optimise planned maintenance schedules in terms of cost, but also in terms of safety. It is not difficult to draw parallels from these maintenance planning problems to those in general maintenance planning of engineering structures, and therefore to see that these techniques could also be useful. However, the focus of these techniques seems to be on the optimised prioritisation of a number of maintenance tasks, rather that on the optimum scheduling based on minimising risk and cost.

4.4.3 Decision-making In Plant Management

The first scientific approaches to maintenance management date from the 1950s and 1960s. At that time, preventive maintenance was advocated as a means to reduce failures and unplanned downtime [38]. Researchers such as Barlow and Proschan [39] and McCall [40] introduced the first operations research models for maintenance optimisation in the early 1960s. In 1960 Mayer [41] and in 1967, Turban [42] found out that little application had been made of these models to real life problems. In the 1970s, condition monitoring came forward, focussing on techniques that predict failures using information on the actual state of the equipment [43, 44, 45]. In the 1980s, the computer was introduced into the maintenance function, initially to facilitate administrative processes, later to collate and present management information.

One of the most important approaches in plant maintenance management, founded in the 1960s is Reliability Centred Maintenance (RCM) [46]. RCM directs maintenance effort to the components whose reliability is critical. RCM is currently probably the most popular method for identifying a cost-effective strategy for plant maintenance. The goal of RCM is to identify the optimal maintenance for each component taking safety, maintenance costs and cost of lost production into account. RCM provides a practical and structured approach for determining a recommended maintenance strategy for each component. However, it cannot be claimed that the strategy derived from RCM is in fact "optimal" particularly in terms of the overall performance of the plant.

Reference [47] describes an extension to RCM claiming to integrate maintenance into the total business system. The method uses utility theory to model different decision objectives, system performance measures to evaluate objectives and plant specific preferences to rank the performance measures. The methodology, therefore, combines a number of well-known models from various fields into a complete and structured approach to quantify the effect of maintenance strategies on the overall production system's performance. The methodology's aim was to provide insight into the relationship between maintenance and economic return and safety. Influence diagrams were used in the communication process. The four main analysis stages were:

- Problem definition, involving defining the main objectives of plant activity along with the system boundaries and the available alternative maintenance strategies.
- Loss function and preference evaluation, measuring the degree of goal attainment with respect to the main plant objectives. Safety, health and environmental objectives are considered along with costs due to maintenance and production loss.

- Dependability modelling involving optimising maintenance scheduling with respect to multiple objectives, focusing on the main aspects of plant activity and providing insight into the relation between maintenance, economic return and safety.
- Compiling results of the risk function based on the expectation of the loss function.

Difficulties arise when combining safety performance measures and economic losses into one overall loss function, especially when considering the value of human life. These safety performance measures also tend to require dependability analyses, which make the total analysis too complex and costly to be practical. However, RCM does not achieve credibility as a maintenance optimisation tool while claiming to prioritise safety without trying to quantify safety and relate it to its associated costs.

Reference [48] presents a simple approach for using two importance measures typically calculated within a standard Probabilistic Risk Assessment (PRA). These are the minimal cutset contribution (which determines the maintenance risk importance based on the equipment risk importance) and the risk reduction importance (which determines the maintenance importance based on the risk impact if the maintenance were not carried out). Maintenance works were classified as either risk important, marginal or unimportant. The identification of risk unimportant maintenance strategies was also useful, because any component failing with minimal risk impact represents a waste of valuable resources. The methods rely on results from a PRA, which could produce subjective results. Both measures also rely on minimal cutsets being identified - for complex structures this could be difficult and time consuming. Reference [49] also presents a similar approach for using two measures calculated as part of a standard PRA. The measures adopted here were the Birnbaum importance measure (which approximates the conditional probability of nuclear core melt given the failure of the system) and the weld importance measure (the product of the Birnbaum importance measure and the probability of weld failure which presents the risk of core melt due to pipe breaks in the system). Therefore, both measures were important inspection planning factors and hence were used as part of risk-based inspection guidance for nuclear power facilities to prioritise inspection for facilities, systems and components.

An important distinction must be made between systems that can only be in two condition states: failure and non-failure and systems that deteriorate continuously over time, for which several non-failure conditions can be identified. In the latter case, it is possible to inspect the system in order to reveal its current condition. A model presented in [50] focuses on partially known continuous-time deterioration processes based stochastically on a finite number of condition levels. A range of possible actions was considered in terms of inspection, repair and replacement strategies over an infinite time horizon divided into discrete moments. The process objective was to minimise the long-term average cost via a policy iteration based algorithm. The deterioration process was converted into a Markov decision process, where the time passed since the last known condition was incorporated into the state description. Costs were determined for operation, repair, inspection and damage for the component. This allows the expected component cost to be evaluated in its expected state when the decision is made. The

objective is to determine the cost-optimal policy, to identify which actions to take in each state. Although it is difficult to obtain reliable condition data, the paper demonstrated a satisfactory application of this method to a real problem, showing the real savings made in an optimal policy versus the periodic inspections.

The data collection problem for such decision models was addressed in [51] by basing the preventive replacement decision on information about the state of the component obtained by monitoring a suitably chosen parameter. The paper also approximates from the infinite time solution to evaluate a finite time horizon optimal age-replacement interval. The infinite time solution described in the previous paper assumes that the renewal system is in a steady state with infinite number of renewals. However, due to a limit usually imposed on the useful life of the component, this situation is seldom true. Limiting the horizon gives rise to unnecessary extra costs, especially if preventive replacement is made near to the end of the useful life of the component. Therefore, this paper proposed correcting the limiting solution to respect the finite time horizon. This method is claimed to considerably simplify and speed up the calculation of the optimal age or diagnostic replacement interval and approximates well to the exact solution.

A counting process approach was adopted in [52] for determining the optimal replacement time, through minimising the long run expected cost per unit time. The counting process was defined as the number of failures in a specified time interval during which no replacement is carried out. The model was based on an observable stochastic process, representing the component's condition with time, assuming no planned replacement in the time interval. Therefore, given the component history up to the current time, and assuming it is still functioning, the probability that the component will fail in the next time interval was calculated. This was then used to determine a planned replacement time by minimising the long run expected cost per unit time.

These models represent a fraction of the hundreds of maintenance optimisation models proposed over the past 30 years. Even recently, researchers have been investigating the reasons why very few applications of maintenance optimisation methods have been made successfully. In [53] it is claimed that it is the user-friendliness of the model rather than its appropriateness that dominates the situation. A frequent complaint of maintenance optimisation models, however, is that they address the wrong type of maintenance. They are often aimed at planned overhauls and preventive replacements, rather than predictive maintenance based on a measured condition. Even if it is possible to find the right model for the right problem, it is still difficult to determine the values of the parameters to use in the model. For example, there is rarely much data available about indirect costs. It can also be difficult to determine statistical lifetime distributions, implying that these models may be based on the wrong concept.

However, a lack of data is not an excuse to set models aside. Decisions still have to be taken and can be based on subjective data or engineering judgement as necessary. Maintenance strategies should not only be tuned to the deterioration and failure processes but to the economic return of the installation. Therefore, to fully optimise the

costs and benefits of alternative maintenance strategies, it is necessary to study the various decision processes and their consequences in detail.

It is concluded that the decision-making methods adopted in plant maintenance decisions are therefore designed to optimise planned maintenance schedules based on historical reliability estimates and projections of deterioration, when this information is available.

4.4.4 Decision-making in the Management of Bridges

The traditional approach to decision-making in bridge management evaluates the options with cost-benefit analyses. However, problems arise differentiating between competing projects, as a simple cost-benefit ratio does not encompass all factors. References [54, 55] developed an incremental benefit cost program that ranks alternatives in decreasing order of their incremental benefit cost ratios. Under limited budgets, this results in near optimal sets of bridge improvement options. The alternative options were ranked by establishing level-of service goals and then determining the deficient bridges with attributes below these goals. The available improvement alternatives were then identified with associated costs, benefits and the remaining or extended life. Finally, the budget was allocated to the least-cost improvement alternatives for all bridges deemed deficient, in descending order of their incremental cost benefit ratios. "Do nothing" was added internally as an option with zero cost and consequence although this is simplistic, as it is likely to have some cost or consequence.

This algorithm only optimises the strategy for unlimited budgets. For many maintenance alternatives and bridges, the algorithm becomes very complex. Furthermore, no account of time was made on deterioration and the improvement needs were assumed to remain constant, hence the above model is only suitable for a short time horizon (1-5 years).

A similar cost-benefit assessment was proposed as the basis for the optimal allocation of resources to bridge repair and maintenance in [56]. This work focussed on the repair or preventive upgrading for earthquake situations, based on optimising resource allocation to reduce system vulnerability. The optimisation was carried out based on the costs of restoring service and the time out of service. The cost of restoring service was optimised by maximising the total savings achieved by each intervention against the cost of no intervention. The time out of service was optimised by maximising the total savings in days out of service for restoration compared to days out of service for restoration following previous interventions. The paper reduced the computational burden of this problem by formulating it as a multi-stage decision process, with each stage independent from the preceding ones and solving it by dynamic programming.

Reference [57] proposed a multi-attribute, life cycle analysis to evaluate the rehabilitation needs of a bridge network in Texas. The size of the annual budget needed for the rehabilitation and replacement activities was calculated over a specified length of time. A full life cycle analysis determining actual expenditures through deterioration curves and predicted cost consequences was considered too complicated. The

techniques were simplified by assuming a fixed useful life of each bridge, after which the structure would need to be replaced and an average rehabilitation requirement at mid-life. A horizon was set for the budget planning exercise and the age of each structure was calculated for every year in that horizon, to categorise each for rehabilitation or replacement (or "do nothing"), evaluating the required budgets for each year. Any backlogs in the work were identified and the work re-scheduled to permit a reasonably constant funding level throughout the planning horizon. The paper proposed an attribute percentile scaling (weighted average ranking) technique to select specific rehabilitation and replacement projects against a common set of multiple criteria. This is a measure of the project's position as a candidate for funding relative to the rest of the projects in the set. Constraints set on attributes automatically prioritise projects if they are exceeded. This scaling process is self-adaptive. If conditions change over time the relative position of the alternative projects can change accordingly.

A key problem in optimal maintenance planning is the time dependent evaluation of a structure's safety. Neither of the previous papers considered the deterioration in structural safety and based the current evaluation of safety according to the statutory codes and standards. The time dependence of the structure's safety is however one of the key problems associated with optimal maintenance planning. This is accounted for in considering current and future structural reliability in [58]. The bridge reliability is measured using the reliability index, β, for a single failure element and for the bridge as a whole [104]. The reliability is assumed to decrease with time due to deterioration but limited by a minimum reliability index. Current and detailed inspections are carried out at fixed intervals updating basic variables based on Bayesian methods [59]. Following these, the reliability is calculated and a decision is made on the need for any subsequent maintenance work or for a more detailed structural assessment. Economics are ignored at this time. Structural assessments are only performed following the identification of nonconformities during a current or detailed inspection. The reliability is calculated and a decision is made on the need and timing of repair work.

This method was developed further in [60]. Again, inspections were assumed to be performed at constant time intervals, to meet regulatory requirements. However, the inspection strategy was formulated so that girders with the largest failure probability were classed in one group and inspected more frequently than others. Girder failure was modelled as a series system with three failure modes of bending, shear and bearing. The optimal inspection strategy with respect to costs was then determined for each girder group. The objective function measured the girder's expected lifetime cost and included the inspection, repair and failure costs. The inspection interval was optimised, constrained by the minimum reliability index, to minimise the total expected cost.

Reliability analysis of bridges and their components was developed in [61, 62, 63] for repair selection within a network. The method was based on inspection methods and inventory database information. A function related the condition state to a reliability index using a normal distribution. The function was found either from subjective estimates or by applying First Order Reliability Methods (FORM) [104]. Bridge elements were combined in series to model the bridge behaviour. In [61, 62], Markov

chains were applied to current condition ratings to obtain probability distributions for element conditions for each year in the planning horizon. This was developed further in [63] so that the condition of one component affected the deterioration rate of another via a transition matrix. Bayesian updating was introduced to update the transition matrices based on inspection results. However, constructing Markovian transition matrices to predict deterioration based on historical data is complex and time consuming.

The risk analysis model developed in [62] measured bridge failure consequences in terms of the detour costs from bridge closure. Other costs, such as expected injuries and fatalities, social and political impacts and the costs of bridge repair were not considered.

A range of optimisation algorithms is discussed in [62], including mathematical programming, search strategies (inappropriate for large problems) and near-optimum solutions (such as genetic algorithms). Under certain conditions, genetic algorithms can achieve optimum solutions, but the near optimum is considered sufficient, as so much of the problem is uncertain. The use of genetic algorithms for risk-optimised selection of bridge repair work is described further in [63].

Another system reliability approach to optimising bridge inspection and repair, in [64], provides a more efficient use of financial resources by ensuring an acceptable level of safety at minimum expected cost. Limit state equations were developed and the reliability of each component was computed separately. The reliability of the bridge system was modelled decreasing over time based on increasing live load and corrosion. A minimum allowable system reliability was established as 2.0. Several repair options including "do nothing", and their costs were established. A discount rate was assumed. All possible repair strategies based on combined repair options and their discounted costs were evaluated for different remaining lives, evaluating the cost optimum strategy.

4.4.5 Decision-making in the Management of Offshore Structures

Experienced engineers have historically made decisions concerning the inspection, repair and maintenance (IRM) of offshore platforms applying judgement supported by deterministic code assessments. However, the ageing population of offshore platforms has prompted more attention to the problem. For example, in 1993, the American Petroleum Institute produced new guidelines to specifically address the reassessment requirements of ageing platforms [65]. This reassessment recognised that existing new design codes allow a probability of failure greater than zero, which should be the same in a reassessment. However, design codes do not always explicitly address risk, but implicitly account for them through design practices such as safety factors, based on experience or on target reliabilities. However, the benefit of accounting for risk in terms of the failure likelihood and consequences was recognised in the management of existing structures, [66]. Structural reliability analysis has been adopted as the main approach to account for uncertainties and evaluate the failure likelihood.

Fatigue and fracture is the principal failure mode in many structural and mechanical systems. However, since fatigue design factors are very uncertain, reliability methods are useful for design decisions [67]. Periodic inspections and repair or replacement can

improve system reliability. This however, can be expensive. The goal of the design process is therefore, to specify a design, inspection and repair strategy to minimise life cycle costs. This paper presented a method for analysing the fatigue reliability and maintainability for a structural system, providing supporting information for an economic analysis to design inspection strategies for minimum life-cycle costs. The inspection process was defined by the probability of detection associated with the given inspection type, the number and spacing of inspections, and the quality of the joint after repair. Monte Carlo Simulation was used to accommodate the complex crack growth and fracture processes into the formulation. The method easily accounts for many possible options with respect to inspection and repairs in a manner flexible enough to address many probability questions concerning fatigue, quickly and easily.

Monte Carlo Simulation was also adopted in a detailed probabilistic fracture mechanics model in [68]. This model's results were used to optimise an in-service inspection schedule. Trade-offs between the reduction in the probability of failure due to inspection and repair of detected defects, against the cost of inspection were considered. Therefore, a Monte Carlo Simulation based fracture mechanics model evaluated the "probability of repair and failure". The costs of each candidate inspection schedule were evaluated with a decision tree. Scenario probabilities were then calculated as a product of all probabilities leading to that scenario and the expected cost for each inspection schedule. The least costly inspection schedule would then be selected.

Reliability analysis of crack growth and inspection effects on reliability updating of crack growth and optimal inspection planning is described in [69]. Leak and fracture failure criteria were considered, corresponding to the serviceability and ultimate limit state respectively. The reliability of non-destructive inspection techniques with respect to no crack detection, crack detection and crack size measurement were evaluated. Methods for reliability model updating from successive inspection events were also developed. Finally, inspection strategies were explored to improve design life reliability.

The problem of defining the optimal inspection time based on cost minimisation is considered in [70]. It suggests that an inspection's effect cannot be quantified immediately after an inspection but at a later assessment time. Therefore, defining the optimum inspection time should be based on the optimum ratio of inspection time to assessment time. The paper considers four main costs in the optimisation process: cost of component failure, inspection, downtime due to inspection, and repair or replacement. Therefore, the optimal inspection time minimises the total expected cost.

One of the main contributors to the use of risk-based decision methods in the management of offshore structures was the CEC funded "Thermie" project [71]. This project developed a knowledge based system incorporating reliability inspection planning methods called "RISC – Reliability based Inspection SCheduling for fixed offshore platforms". The RISC programme pulled together fatigue and fracture mechanics growth modelling techniques, advanced structural reliability methods, material, stress concentration factor and sample inspection reliability databases and

scheduling algorithms incorporating resource constraints [72]. This whole system was controlled by a knowledge-based system to provide a rational and workable set of IMR schedules for each structure. The optimal inspection and maintenance plan was based on minimising the expected total costs for maintaining the structure throughout its anticipated lifetime [73]. This allowed different maintenance plans to be compared, constraints to be enforced and hence a rational plan to be chosen. The inspection reliability, in terms of crack detection and sizing was evaluated by modelling different inspection method qualities by assigning different crack detection probabilities.

A ranking algorithm that quantified a number of weighted selection factors reduced the number of joints requiring detailed consideration. The weights determined by the operator include legal and safety requirements; joint criticality and location; ratio of past life to predicted fatigue life and earlier inspection results. Thresholds were set for certain criteria based on acceptance limits. Structural reliability techniques were used to evaluate failure of the main joints according to two main failure criteria, accumulated damage and fracture failure [74].

IMREL [75] is a similar program for Inspection and Maintenance planning of fixed offshore structures using RELiability based methods. IMREL assumes a particular inspection and repair scheme and calculates the associated cost function, for a set of plans within the scheme. The decision-maker has to check that the reliability of the particular joint is acceptable and then chooses the plan with the smallest cost function value. A minimum acceptable reliability index of 3.0 was selected.

A thorough formulation of reliability-based optimisation in structural engineering based on classical decision theory is presented in [76]. The main focus is on reliability based optimal design of structural systems with component or systems reliability constraints. Adaptations of the model are also presented for reliability based optimal inspection planning and reliability based experiment planning. Solution strategies are found by applying first order non-linear optimisation algorithms but considering sensitivity analysis and optimisation stability. For reliability based optimal inspection planning, the optimisation was formulated in terms of the expected cost of inspection, repairs and failure. The optimisation was constrained by the changing reliability index over time, remaining greater than a specified minimum reliability index. However, the authors proposed that the constraint on minimum reliability is already incorporated into the objective function through the expected cost of failure.

Reference [77] proposed simplifying this model, to make it more practical for use. First, only the time and quality of the next inspection could be optimised. Secondly, the inspection planning could be based on reliability considerations alone. Thirdly, the decision tree branches could be evaluated in terms of probabilities for no repair events for high reliability situations, due to the very few repairs that would be expected.

The decision-making methods developed and adopted in structural engineering have been progressed in different areas to begin to account for the results of structural reliability calculations and probabilistic degradation models. Developments to incorporate multiple criteria into the decisions have, however, been very limited.

4.4.6 Decision-making In Pipeline Engineering

To date, very little research and development has been carried out in risk-based decision-making for the management of pipelines (onshore and offshore). The following summarises the limited work that has been achieved. Two main categories of risk-based pipeline management techniques have been developed over the last ten years, qualitative index based systems and quantitative risk analysis based systems.

The qualitative risk index systems such as those presented in [78, 79] assign subjective scores to the factors thought to influence the failure probability and consequences. The scores are then combined to give a risk index, which provide relative rankings, but do not indicate the risk acceptability. Therefore, there is no guidance regarding the necessity of risk reduction measures. The risk indexes are also based on a number of subjective evaluations, which introduce inaccuracies and inconsistencies.

The quantitative risk analysis approaches, such as those presented in [80, 81, 82], estimate the level of risk based on direct estimates of failure probability and consequences. However, these papers consider single consequences such as risk to human life and economic risk. They do not consider environmental damage or multiple consequences together. Furthermore, the failure probability estimates tend to be based on historical data only. This is a problem due to the rarity of pipeline failures. In addition, the effect of maintenance on failure probability tends to be subjectively accounted for, rather than through quantified historical inspection results.

A combined method using both qualitative and quantitative risk assessment techniques was presented in [83] for prioritising pipeline inspection, maintenance and repair. This method provides a more detailed assessment than the relative risk scores described above. This allows clear actions to be defined. The scheme prioritises inspection, maintenance and repair using available information and provides data on the most likely damage a line will suffer and the possible extent of the failure consequences. This can then be used to investigate the most appropriate action to reduce the failure risk.

One paper that aimed to address the issues of combining different failure consequences into one measure and modelling the effect of maintenance actions is reference [84]. The risk-based decision framework proposed was based on [23] using influence diagrams to solve the decision problems. Three decision criteria were identified as cost of failure, number of fatalities due to failure and the residual spill volume after clean up. The paper recommends initially evaluating the best solution using a cost optimisation routine constrained by life safety and environmental damage, optimising on the option with the least expected cost. This removes the need for assessing trade-offs between cost and safety. However, the result obtained may not be overall optimal from the operator's point of view, especially for existing pipelines, as it may force the operator into an expensive solution in order to meet the recognised safety criteria. In these cases, the paper recommends defining a utility function to explicitly quantify the trade-offs between cost, safety and environmental damage. The optimal solution is then the one that maximises the expected utility. The limitation for this model is the potential reluctance of decision-makers to address these trade-off issues directly.

The decision-making methods developed and adopted in the pipeline industry have begun to draw on some of the methods described previously, however, experience in their application and hence their refinement and applicability can still be improved.

4.4.7 Summary of key points

This overview of decision analysis applications has reviewed the methods adopted in six different industries to support risk-based decisions. The industries that have been investigated are military, aviation, power plants, bridges, offshore structures and pipelines. This overview has briefly described the key principles of the decision methods that have been adopted in the different fields. The limitations and strengths of each method have been discussed. This overview has shown a range of methods and models available to support decision-making. Each method could be useful and helpful to the decision-maker in the right context. For example:

- Military decision-making methods are useful in qualitative, high level decisions or in those involving significant stakeholder conflicts such as in conceptual design.
- Methods used in the aviation industry are useful for optimising planned maintenance in terms of cost and safety such as developing inspection /maintenance strategies at the design stage, when minimal data is available, but the solution can be optimised.
- Plant maintenance decision methods are useful for planning maintenance based on historical reliability and deterioration estimates. These help to update inspection, maintenance and repair strategies with new inspection and analysis results.
- Decision methods used in the management of bridges and offshore structures are useful for incorporating structural reliability and deterioration model results and begin to address multiple criteria issues. These could also help update inspection, maintenance and repair strategies with new inspection and analysis results.
- The methods developed in pipeline engineering have begun to draw on some of the above principles; however, they have only been applied to very limited problems.

A number of systematic decision processes were presented in this overview similar to the one suggested by Keeney and Raiffa [23], discussed in Section 4.3. Table 3 shows a comparison between each process. This table therefore indicates the rationality of adopting Keeney and Raiffa's process as the basis for the proposed risk-based decision process and the thoroughness of the modified proposed risk-based decision process.

Keeney & Raiffa [23]	Raiffa [22].	Military Appreciation [28]	Multi Attribute decision methodology [99]	Extended RCM [47]
Pre-analysis –identify the problem and the viable alternatives	List viable options available for gathering information, experimentation and for action.	Study the existing situation	Initiation - identify objectives, assess their relative importance and determine risk acceptance criteria.	Problem definition – define main objectives and problem boundaries and identify alternative maintenance strategies
Structural Analysis – structure decision problem and identify what choices can be made now and what choices can be deferred; what information needs to be gathered or experiments carried out. Construct a decision tree	List the events that may possibly occur	Specify the aim to be attained.	Hazard analysis - identify the hazards threatening the objectives, identify generic scenarios, containing the hazards, and assess the criticality of each risk scenario.	Evaluation of the loss function and preferences –consider the attainment of the safety, health and environmental objectives with maintenance costs, lost production and management preferences
	Arrange in chronological order the information you may acquire and the choices you may make over time.	Examine and draw reasoned conclusions on all relevant factors		
Uncertainty Analysis –assign probabilities to the branches on the decision tree.	Judge what the chances are that any particular uncertain event will occur	Consider all practicable courses of action	Risk assessment - collect relevant data, verify the criticality of each risk scenario, classify each risk scenario and calculate the overall risk-based on all risk scenarios.	Dependability modelling – optimise maintenance scheduling with respect to multiple objectives.
Utility or Value Analysis –assign utilities to consequences associated with paths through the decision tree. Maximise expected utility to determine choice.	Decide how well you like the consequences that result from the various courses of action open to you.	Decide on the best course to attain the aim	Countermeasure analysis – identify all possible countermeasures to each risk scenario and evaluate their costs, effects and utility. A sensitivity analysis can be carried out.	Compilation of results – determine the risk function based on the expectation of the loss function
Optimisation Analysis – optimise expected utility.		Make a plan to implement the course	Countermeasure deployment –implement and monitor the effectiveness of the selected countermeasure	
		Check all reasoning and the practicality of the plan.	Post-implementation evaluation – evaluate the effectiveness and feed back lessons learnt into the decision process.	

Table 3 Comparison of the stages in Keeney and Raiffa's decision process with the stages of alternative decision processes

However, it is not possible to identify any particular approach described in the above overview as suitable to support all risk-based decision-making in the management of structural assets. There are obviously limitations in the availability and flexibility of methods so far adopted in industry. It is therefore necessary to take the research back to the basics of decision analysis and review the range of methods developed in the decision sciences and operations research.

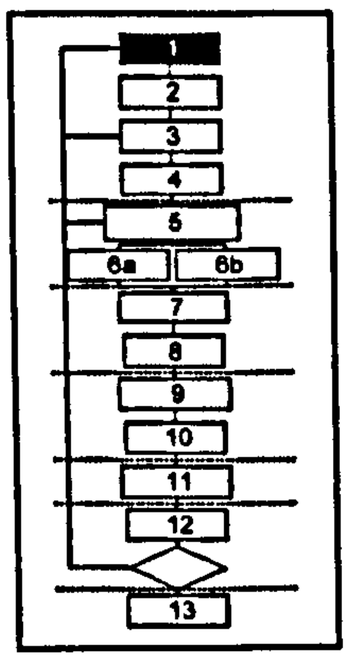
4.5 A Review of Available Risk-based Decision Theories

The aim of this section is to take the research back to the basics of decision analysis. The range of decision methods developed within the decision sciences and operations research are reviewed to identify models that can support decision-making at each stage of the proposed decision process. Therefore, the proposed decision process, presented in Figure 4, has been used as a basis for the following review.

4.5.1 Problem Definition

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

4.5.1.1 Identify problem or opportunity



The decision-making process starts with an individual noticing either that something is amiss or that a likely decision opportunity exists in the organisational environment. This may not always be based on evidence, but sometimes on intuition [85]. This awareness may not result in immediate action but in a time of reflection, possibly involving minor activity to make the problem go away. Following reflection, or evidence accumulation, the decision-maker becomes convinced of the need to make a decision. Decision identification is the central "node" shown in the entity diagram in Figure 1. Common sense suggests that the first task in evaluating a decision problem is to determine what the problem is. However, defining the problem is more complex, especially if it requires multi-disciplinary inputs or conflict resolution.

It does not 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. Therefore, the decision-maker should initially seek to identify and understand the basic need that the decision is to fulfil. This should be done from all relevant viewpoints, which may identify different perceptions of the true problem. 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.

Examples of situations giving rise to the need for decision analysis could include:

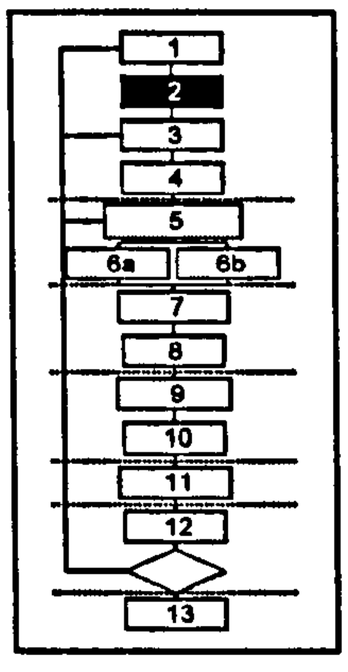
- A problem to prioritise projects for funding due to insufficient funds for all needs.
- An opportunity to invest surplus funds at a good return, due to excess profits.

Example problems covered by this research, from structural asset management, include:

- Selecting the best inspection, maintenance, or repair strategy for a structure.
- Prioritising components for inspection, maintenance or repair to optimise fund usage.

If the problem or opportunity 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.

4.5.1.2 Identify Stakeholders in the decision



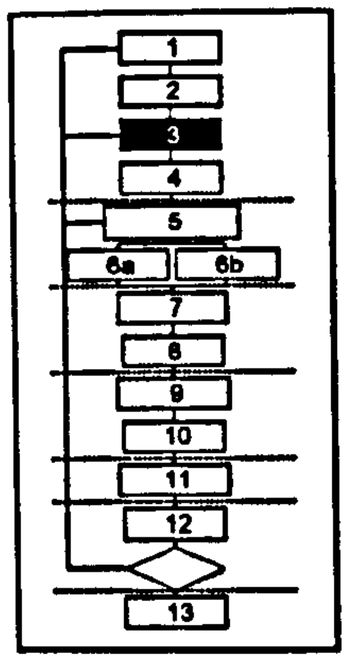
Keeney and Raiffa [23] briefly mentioned the possibility of more than one decision maker being considered, or of other stakeholders having an interest in and an influence over the decision process. However, they ignored this problem, to keep the theories simple. Von Winterfeldt and Edwards [86] also explicitly ignored the problem. However, it is now understood that this is a significant part of the decision process as shown in Figure 1. If this is not addressed, significant problems could be encountered later on in the decision.

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 usually need to be sought. On a formal level, a committee can be formed consisting of representatives from the organisation who are expected to represent departmental interests as well as contributing their own views. Committees may still, however be influenced by other external parties (or stakeholders) who would also need to be consulted. This results in all members of the decision body (whether a committee or a set of independent advisors) having different degrees of influence in the decision.

It is through the decision body that the organisation's objectives are interpreted and translated into evaluation criteria. This means that the decision stakeholders not only make the choice itself but can also control the options and information considered. The overall objective of accounting for all stakeholders in a decision situation is to obtain consensus and ownership. When identifying the stakeholders, there can be a tendency to concentrate on an organisation's formal structure. It is, however, necessary to identify informal stakeholder groups and to assess their importance. For internal 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 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 and stakeholders to be considered in our example problem have already been discussed in Section 3.3.1. Not all people with an interest in the decision-making process are experts with respect to all aspects of the problem situation. Group

decision techniques can, therefore, be adopted to allow the expertise, preferences and relative importance of each stakeholder to be accounted for. The different group consensus methods can be broadly grouped into sharing, aggregating and comparing methods [87] and involve negotiation, joint scoring systems and voting techniques. Each method could be appropriate in different situations depending on the stakeholders' strength of feelings and their relative power.

4.5.1.3 Identify viable alternatives



The decision alternatives are the various courses of action between which the decision group must choose. 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. Frequently, decision analysis literature has assumed that the available alternatives are provided for the decision-maker to choose between, or are at least easy to find. However, it is common for problems in decision-making to stem from a failure to produce sufficient feasible alternatives. De Bono [88] 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.

Decision problems can be classed as two main types, as follows:

- The evaluation problem, is concerned with selecting 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 identifying 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. However, as stated initially, this review is concerned only with decisions involving a finite number of alternatives. This form of decision problem will not be explored further here; for completeness, a brief summary of the differences is presented in Appendix 1.

In some decisions, the alternatives are obvious when the decision problem is defined. However, in other decisions, the available alternatives are not immediately apparent. In this case, for the evaluation problem, it is not always straightforward to generate them.

Gardiner [89] 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?" This is because the alternatives on hand cannot be compared 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 to show how the known options score against all possible options.

However, the problem with this method is that some of the possible alternatives that could be produced in the decision space may not be feasible. This could result in generating too many alternatives to handle and it may prove difficult to avoid or recognise those that are infeasible. This could give a biased view of the alternatives that are known, causing excessive resources to be spent generating more alternatives to produce a more balanced decision space.

Other techniques for generating alternatives include attribute listing, brainstorming and focused object linking [85].

Attribute listing is an analytical technique similar to the approach proposed by Gardiner, described above. The major decision attributes under consideration are identified, such as size, cost, shape, etc and then each attribute is altered in as many ways as possible. Each alteration creates a potentially different solution. This can result in a vast number of alternatives, which may then become difficult to handle.

These solutions would then have to be screened for feasibility. 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 screening methods increases with ease of use or speed in eliminating alternatives, however a good screening method should also be reliable with respect to the alternatives that it keeps and those that it rejects. Any screening method, according to Walker [90] should possess two properties: no very good alternative should be removed and 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 best known idea generation method and is classed as an association technique. Brainstorming sessions would optimally involve about 8 people and be controlled by very precise guidelines. These include aiming for as many ideas as possible, recording all ideas, building on other's ideas and banning all criticism and judgement. Without these, the session can become unstructured and biased.

A derivative of brainstorming is "brainwriting" [91], where participants write their ideas on paper instead of contributing them to a communal list. The leader generates a separate list in advance, which is held the centre of the group. Any member that runs out of ideas exchanges his list with the central one and continues to generate ideas there. It is suggested that each participant is stimulated by ideas picked up from the central list. In addition, participants concentrate better without being distracted or influenced by other group members. However, this isolation could also limit lateral thinking.

Focused Object Linking [85] is a forced relationship technique based on establishing 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. One 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. Forcing these relationships can lead to many new ideas.

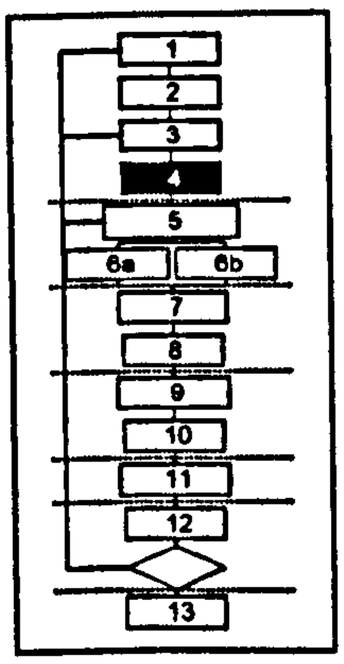
Von Winterfeldt and Edwards [86] describe a method known as means-end analysis developed from artificial intelligence techniques by Pearl [92]. This method defines the problem as the difference between a desired goal state and the current state. Sub-problems are defined by the dimensions on which the current state falls short of the Goal State. The problem is then solved by dimension by sequentially inventing actions to reduce the difference between the current and the Goal State. This process is thorough, but may also become tedious if there are many alternative increments.

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 [93, 94, 95]. 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, [96, 24].

In the current example, a bridge has been assessed to have insufficient capacity to carry the current traffic load, should be strengthened to full capacity, repaired to maintain the current capacity but protected against further deterioration or 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 is an evaluation type decision scenario, 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 methods could introduce new alternatives not normally considered.

4.5.1.4 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 should be comprehensive and measurable representations of the decision-maker's objectives used to describe the different alternatives. They can be objective (e.g. considering the cost of repair and the risk of collapse resulting in death or injury) or subjective (considering environmental damage and disruption to traffic and local business).

The formulation of decision objectives supports the decision process by forcing the decision group to think about the requirements for an acceptable solution and stimulating interest by providing a feeling of accomplishment. It also serves as a reference against which possible solutions can be measured and provides consensus on what is trying to be achieved.

Keeney and Raiffa [23] 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 objectives are likely to influence the structuring process.

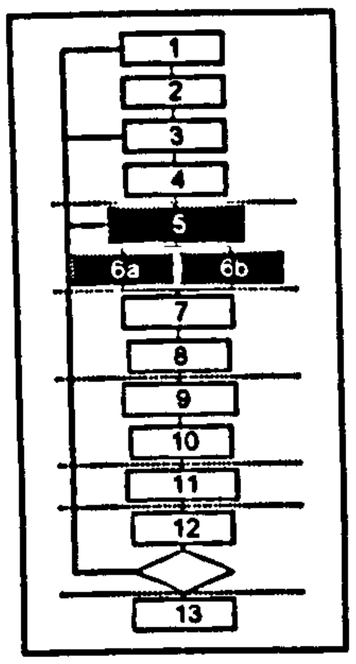
In an evaluation problem, the decision alternatives are likely to be known, but the decision criteria made may not be clearly defined. In this case, a "bottom-up" approach can be adopted to determine the decision criteria [7]. A number of different techniques can be used to analyse some of the alternatives, 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 should be defined in order to achieve 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. The decision objectives would be formulated based on these criteria. 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.

Before moving on to the next stage of the decision process a number of checks should be made to ensure that the objectives have been clearly defined. They should also be consistent and agreed by all members of the decision group. This allows the decision group to understand what is being achieved. Objectives should also be "sensible" [85], such that they are needed, practically achievable, relevant to the overall organisation objectives and measurable so that their achievement can be known. This is similar, but more subjective, to the "clarity check" proposed by Howard [97]. This concept was introduced to ensure that all stakeholders in the decision process have achieved 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 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. This removes any vagueness in the decision criteria and alternatives and ensures that all stakeholders understand the common and distinct value perceptions held by each other.

4.5.1.5 Structural Analysis



In many decisions, it is necessary to break the main decision into smaller parts. Depending on the decision problem this can mean subdividing the decision on different bases, depending on which most helps to solve the problem. There could be a series of decisions to be made over time, where each sub-decision requires a follow-up action. Alternatively, the selection of one alternative could open up a whole series of other alternatives or events. A decision matrix, a decision tree or an influence diagram can be used to represent these scenarios.

A decision (or outcome) matrix models straightforward decisions under uncertainty in a way that makes the options and the possible uncertain outcomes explicit to the decision maker. The matrix also defines a simple decision rule to choose between the alternatives. This method is limited to one off decisions and cannot take account of the sequential nature of decision-making.

The decision tree format, in contrast, represents sequential decisions and traces back the consequences of future decisions 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 [98]. Figure 5 shows the decision tree for the 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.

An influence diagram provides a simpler graphical representation of a decision problem. The decision problem elements (the choice to be made, uncertain events and the value of outcomes) are shown as different shapes. These shapes are then linked with arrows to show the relationships among the elements [24]. The same example problem as before is presented in the form of an influence diagram in Figure 6.

Influence diagrams are very useful for the structuring phase of problem solving for large or complex problems. Decision trees show more of the detail of the problem but can become complex and out of hand [99]. Whichever method of representation is selected should not affect the ultimate decision, as both are interchangeable.

The structuring stage can also be used to define the decision criteria in more detail. For example, the Analytic Hierarchy process [100] helps the decision-maker arrange criteria into a hierarchy with the lowest criteria as measures for the criteria in the level above.

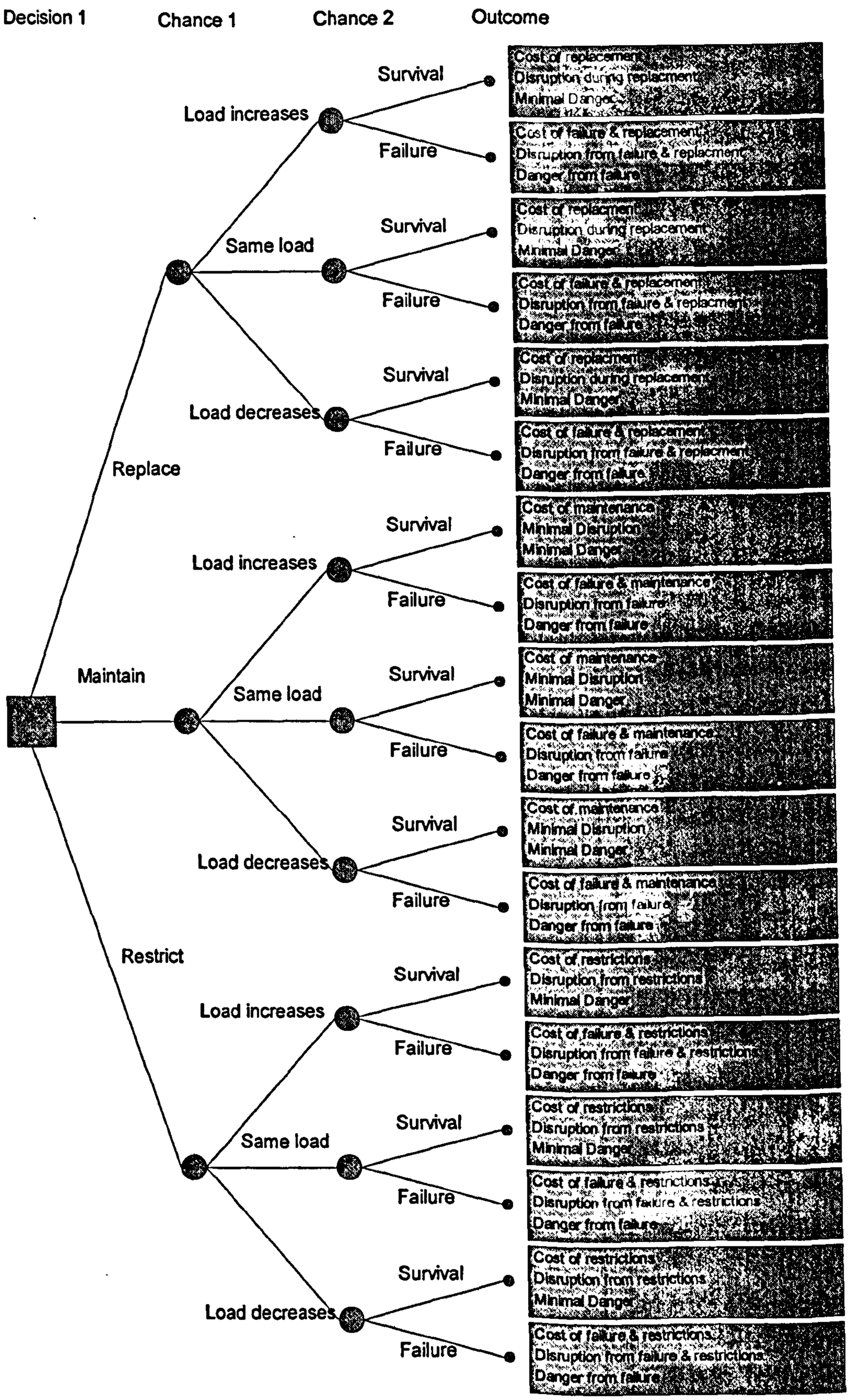


Figure 5: Example Decision Tree

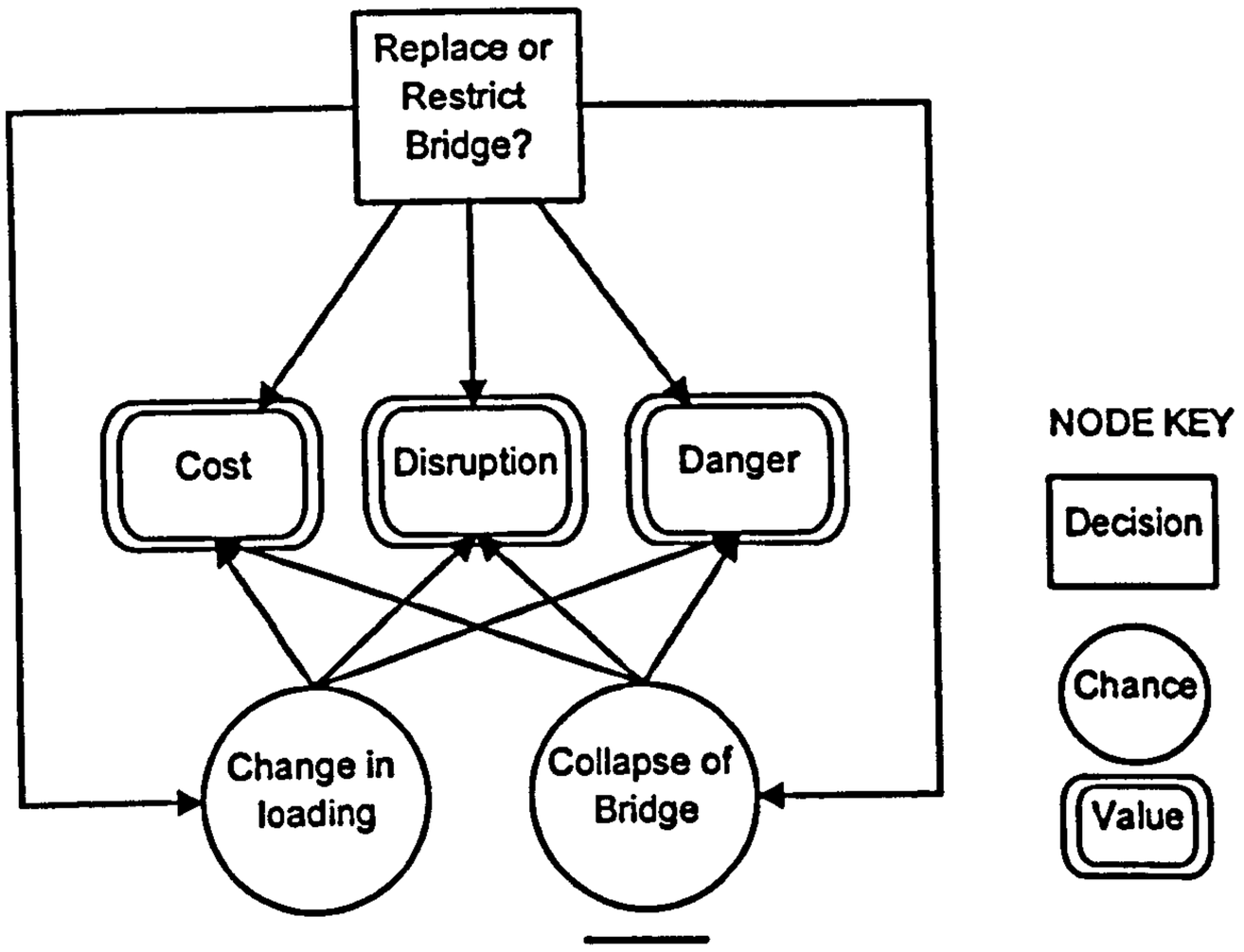
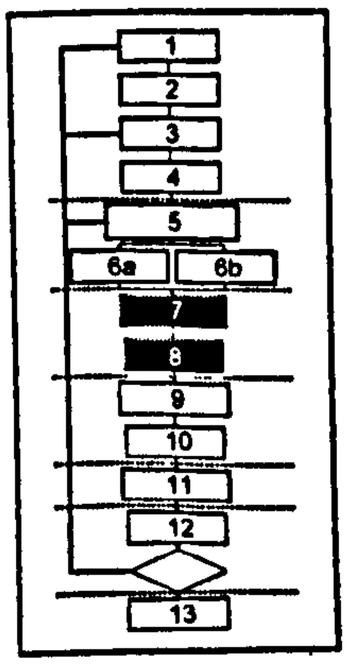


Figure 6: Influence Diagram of Example Problem

The structuring process, especially with influence diagrams, supports the decision-maker in identifying all possible alternatives and 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 [24]. 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 may be too complicated 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 guide the decision maker in formulating the problem. Several of the most common tools are discussed in Section 4.6.

4.5.2 Uncertainty and probabilistic analysis



Since uncertainty is such a critical element of many decisions it is necessary to consider this in the decision modelling process. Uncertainty analyis 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 [15]:

1. Certainty: The situation when outcomes are certain plays a very small role in 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, most people consider it 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 [101].
3. Risk: The decision maker makes 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 cannot 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.

Decision analysis literature makes very little mention of the formal handling of uncertainty. 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 [102], as follows:

1. Choose the uncertain variables having significant bearing on the decision.
2. For each variable, estimate the probability distribution most closely reflecting the decision maker's degree of belief of 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 distribution and combine them to determine a value for the measure of outcome.
6. Repeat (5) many times until a distribution for the measure of outcome is formed.
7. Repeat (1) to (6) for each option under consideration.

This method, from the field of quantitative risk assessment, 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, an earlier criticism would have been the significant computation time required, however, this is no longer such a problem with current computer technology.

The literature concerning probability theory and structural reliability theory handles uncertainties more thoroughly, as described below (although subjective probabilities can still be used).

The main decision objective is to minimise the risk of structural failure. The main definitions of risk were described in Section 3.3.3 where the proposed definition of risk to be adopted in this risk-based decision process is:

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

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.

A codified design or assessment uses a number of partial safety factors to guard against extreme variations of the variables ensures the safety of a structural component [103]. Safety under a particular limit-state is checked using a design compliance equation of the form

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

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 component capacity 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.

Three main types of uncertainty could be encountered in a decision problem [104]:

1. 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 practical and economic limitations of taking measurements, uncertainty will remain, this is statistical uncertainty.
2. Statistical Uncertainty: Statistical uncertainty arises from inferring probability distributions from sets of sample data. However, since very large samples are required to reliably estimate the parameters of a distribution, uncertainty remains. This uncertainty is reduced as the number of samples increase, but is never completely removed. This therefore, is solely a result of lack of information.
3. Model Uncertainty: Predictions of many different kinds make use of mathematical models that relate required output quantities to the available input quantities. These models may 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 will be based on some level of simplifying assumptions and so uncertainty will remain. These uncertainties can have a significant effect on reliability.

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 is 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 have to be developed for each failure mode and each uncertain variable within these models has to be modelled as a random variable. The probability distributions associated with each random variable should be based on as large a sample set of data as possible. For some variables, this will not be possible, so subjective probability distributions 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

$$Z = function(f_k\ ,\ \mathrm{g},\ d)\cdot B_R - \left(effects\ of\left(Q_D + Q_{SDL} + Q_L\right)\right)\cdot B_Q \qquad \textbf{Equation 2}$$

and the probability of failure is calculated as

$$p_f = Probability[Z \le 0] \qquad \textbf{Equation 3}$$

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 are introduced to model, respectively, the uncertainty in the capacity calculations and in the analysis method used for calculating the load effects.

The probability of failure as expressed in Equation 3 can in principle be calculated using any one of the three methods: Numerical integration, Monte-Carlo simulation and FORM/SORM methods.

Direct numerical integration is only feasible if there are less than around five basic variables. The 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 [104, 105]. Commercial structural reliability software, such as STRUREL [106] is available to support this.

The probability of failure (for each failure mode) is calculated for each alternative in the decision tree, so takes into account the loading reduction, the resistance increase or the continued structural deterioration. The exact effect of these measures is unknown, so these uncertainties are also included. The analysis gives the probability of failure p_f and the "reliability index" β, related to p_f through,

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

Equation 4

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

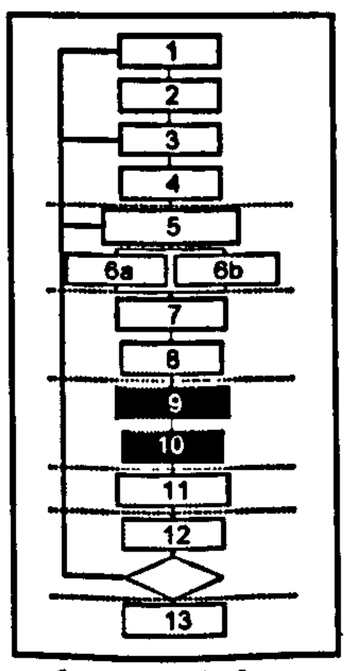
A reliability analysis also provides "sensitivity factors" which express the relative importance of each basic random variable's uncertainty to the computed probability of failure of the component. In addition, the gradients of the reliability index with respect to the mean value $\partial\beta/\partial\mu_i$ and the standard deviation $\partial\beta/\partial\sigma_i$ for each random variable X_i 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 gives the "most-likely" combination of variable values that would cause component failure.

To evaluate the failure consequence magnitudes, the different consequences must be identified. The most common consequences considered are financial, injury, fatalities and environmental consequences. However, others may be accounted for subconsciously including social, political and commercial consequences. It is very difficult to predict the magnitude of these consequences and to identify a useful scale to measure each consequence against.

Traditionally, each consequence is converted to a financial scale, which causes problems when trying to put a value to a life, the environment, society, etc. Multi-criteria decision analysis means that all these consequences do not have to be converted to a common scale, but can be assessed in their natural units. 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 structural failure risk for each consequence can then be derived. These individual risk values can be represented on each branch of the decision tree [107] but they should not be combined into an overall risk 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 [108].

4.5.3 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' preference between the decision criteria, i.e. is cost more significant than safety? Ordering or weighting the decision criteria can handle this type of preference. Therefore, this type of preference is called weighting.

The other type of preference concerns the decision maker's tolerance to the decision consequences. Traditionally, this is defined using the concepts of value or utility. Utility is the preference between a sure consequence and a gamble [86] (e.g. how much the decision-maker is prepared to sell a gamble for). This accounts for the degree of risk aversion of the decision-maker. Value is the preference for gain or loss of a sure amount compared with a different sure amount [86] (e.g. how much worse is a cost of £1m than £1k, and the 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 [86]. Von Winterfeldt and Edwards argue, however, that the distinction between the two types of preference function is spurious because nothing is certain, so a value function for a certainty is really for a low risk gamble [86]. Risk aversion can be easily accounted for in utility functions and by marginally decreasing value functions. Finally, 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 known 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. There are two distinct types of approach for the evaluation problem: aggregate value function approaches and outranking approaches [7].

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. Preference structures are elicited from the decision maker by comparing pairs of preferentially independent attributes assuming the other attributes are fixed. Detailed questioning derives a relationship for each pair of attributes, to show how much of one attribute the decision maker will give up for a certain amount of the second attribute at different values of the first attribute. This method can derive very detailed relationships (utility functions) between attributes allowing the 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 [23].

- Simple Multi-Attribute Rating Technique

This technique is a simplified multi-attribute utility method. It derives multi-attribute utilities (reflecting the "attractiveness" of an attribute's gain or loss) for the decision criteria based on simple rating methods. The technique involves ten steps to identify the important criteria and then ranks and weights them. A scale of 1-100 is derived for each criterion for each possible outcome and each alternative is scored. Simple additive aggregation trade-offs between attributes calculate the total utility for each alternative. The alternative with the highest total utility is selected. This method is not theoretically elegant, but it is easily taught and derives values one criterion at a time [109].

- Inverse Preference Methods

These methods apply preferences to a sample alternative 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 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 by Lagreze and Shakun [110] and POLICY by Rohrbaugh and Wehr [111].

- Analytic Hierarchy Process

This technique derives weights to reflect the relative importance of the different criteria. The criteria are arranged into a hierarchy so that the lowest level criteria are measures

for the next level criterion above. Pair-wise comparisons elicit individuals' preferences for each criterion 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 criterion over another. This can be carried out in the form of a questionnaire. From these results, 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 is a consistency index for the decision-maker's preferences [100].

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 4.

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

Table 4: Calculating the weighted probability distribution for each criterion utility

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 for that alternative.

Outranking Approaches

The outranking methods, principally developed in France and Belgium, consider that in some situations, 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 [112, 113] and PROMETHEE developed by Brans, Mareschal and Vincke [114].

- The ELECTRE IV method

Each pair of alternatives is initially compared to determine the strength of each outranking. Two groups are identified, those that 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 time consuming and complex process is not very attractive to many decision makers.

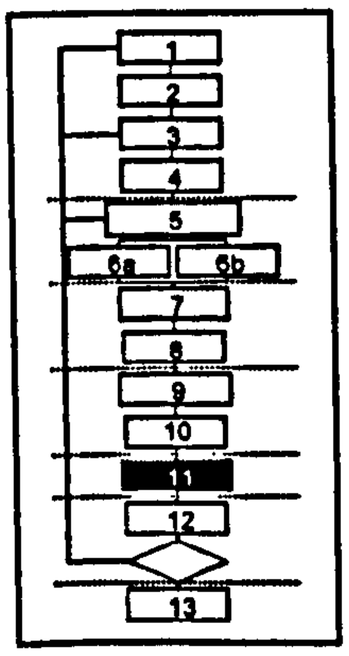
- The PROMETHEE Method (Preference Ranking Organisation METHod for Enrichment Evaluations)

This method includes two phases: constructing an outranking relationship for the decision space and exploiting the relation to maximise the decision criteria. Initially, 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 outranking relation is exploited 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. Then all possible actions can be proposed to the decision maker to resolve the decision problem.

Brans, Vincke and Mareschal [114] carried out tests to identify the influence on rankings when small deviations are introduced in preference values, for both methods. They showed that PROMETHEE is more stable than ELECTRE as small deviations do not affect the rankings while large deviations do. They also found that the evaluations are less stable for extreme disagreement between criteria.

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

4.5.4 Selection of "best" alternative

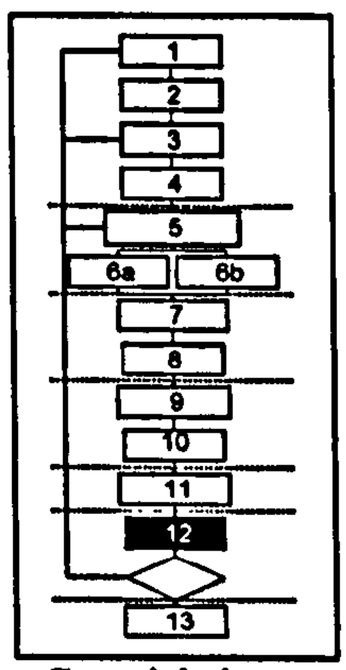


Once the attributes have been scored and weighted, several methods are available to select the best alternative. In the analytic hierarchy process, once the weighted scores for each attribute have been determined, they are summed for each alternative as shown in the final column of Table 4 and the alternatives are then ranked according to their total weighted scores. The "best" option is the one with the highest score.

Other methods are available, although they do not 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 [115], this is a very simple view of risk and was criticised by Howard [116] 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. In addition, the consequence space is sometimes not continuous

and so the outcome will either be very good or very bad. However, expected value remains a concept that is straightforward 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 considered. Other "informal" risk evaluation methods include: dominance theory [117]; the criterion of pessimism [118]; the criterion of least regret [119]; the criterion of rationality [120]; lexicographic ordering [121]; the Efficient Frontier (which originates from the Capital Asset Pricing Model, [122]); the use of artificial constraints; and the 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.

4.5.5 Sensitivity Analysis



Sensitivity Analysis answers "What matters in this decision?" Sensitivity analysis should be an integral part of the decision modelling process, however, no "optimal" sensitivity analysis method exists for decision analysis [24]. The flow chart in Figure 4 shows how sensitivity analysis can feed back information to different stages in the decision process, even to the problem identification. The question at this stage is "Are we solving the right problem?" The answer does not require quantification but in does require careful thought and protects 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 or a more detailed description of the possible outcomes. It could even mean the problem is represented in a different way.

Sensitivity analysis can also help determine which variables are important and therefore which uncertainties would be best refined. Graphical techniques have been developed within decision analysis to help determine the relative importance of different variables.

Finally, sensitivity analysis can be carried out to determine the diversity of decision makers' preferences, their effect on the consensus weightings and the sensitivity of the outcome to any conflicts.

4.5.5.1 Tornado Diagrams

These show how much an alternative's value varies with changes in a specific attribute [97]. Each alternative's attribute's mean value is assumed as the base value, and then each variable is evaluated between its minimum and maximum to determine how much that alternative's final decision value would change. Considering the example presented before, the effect of the loading, strength and injury probability uncertainty on the total cost, is considered in the context of the bridge restriction alternative. This example is shown in Figure 7 and shows that the cost is most sensitive to the bridge loading.

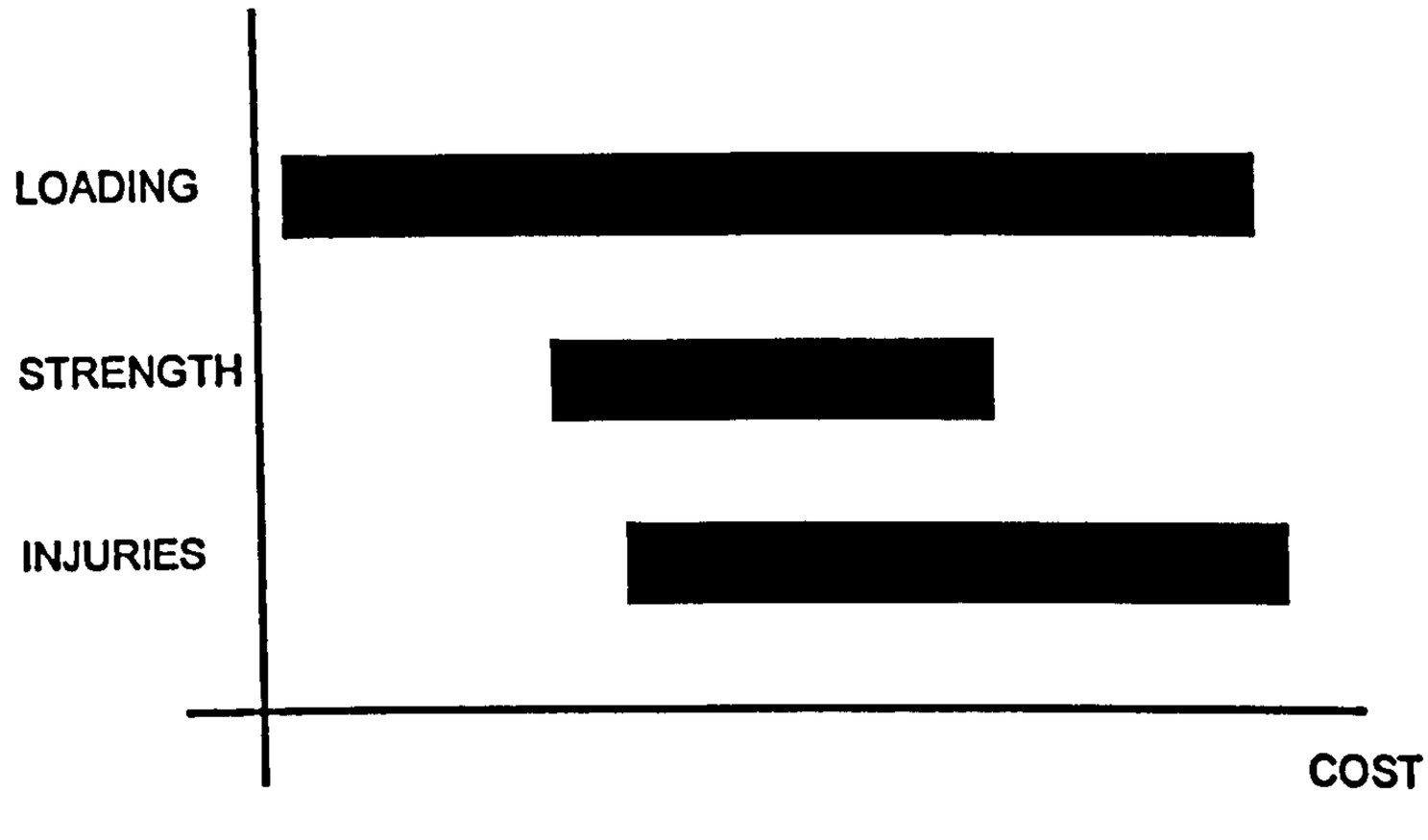


Figure 7: Example Tornado Diagram

4.5.5.2 Two Way Sensitivity Analysis

Tornado diagrams identify the effect of changing one variable at a time. We may want to consider, though, the impact of several variables at one time. The Two-way Sensitivity Graph is a graphical technique that considers the interaction of two variables. The same example problem is shown in Figure 8 and considers the cost sensitivity to loading and injuries [24]. The diagram shows a rectangular space representing all possible values that the two variables could take. A relationship is then plotted showing the effect of varying these two variables on the total cost (a constant cost line).

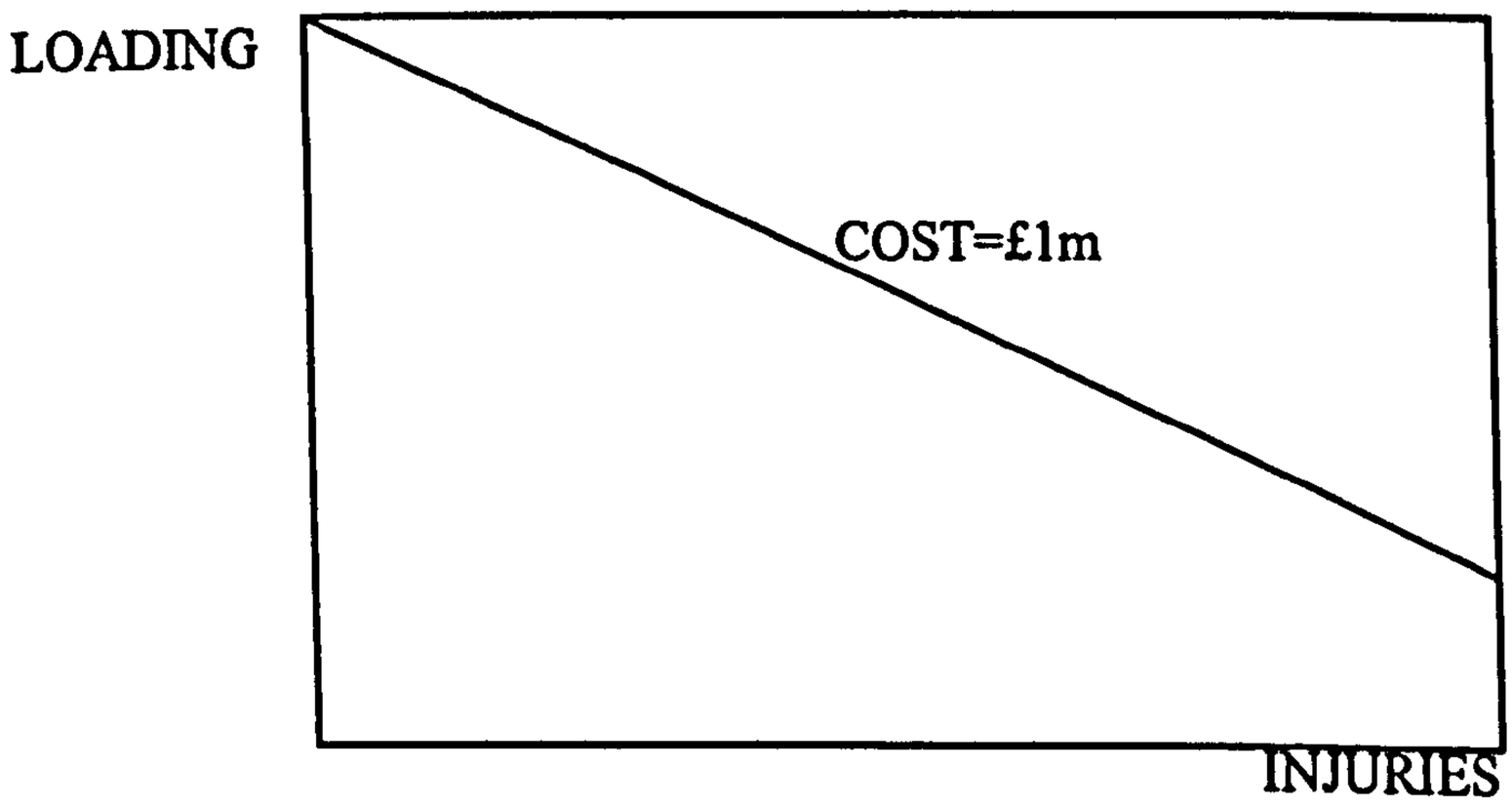


Figure 8: Example Two Way Sensitivity Graph

4.5.5.3 Strategy Regions

A two-way sensitivity graph for two uncertain variables can show for a decision between two alternatives, the conditions of uncertainty when the expected value of alternative 1 is greater than that for alternative 2 [24]. An example is shown in Figure

9. This indicates when different strategies are optimal. This plot can provide guidance in determining how much effort is needed to model uncertainty in the decision problem when the decision-maker is uncertain of the probability of the two uncertain variables. However, for large numbers of uncertain variables and alternatives, the number of graphs required would become unmanageable.

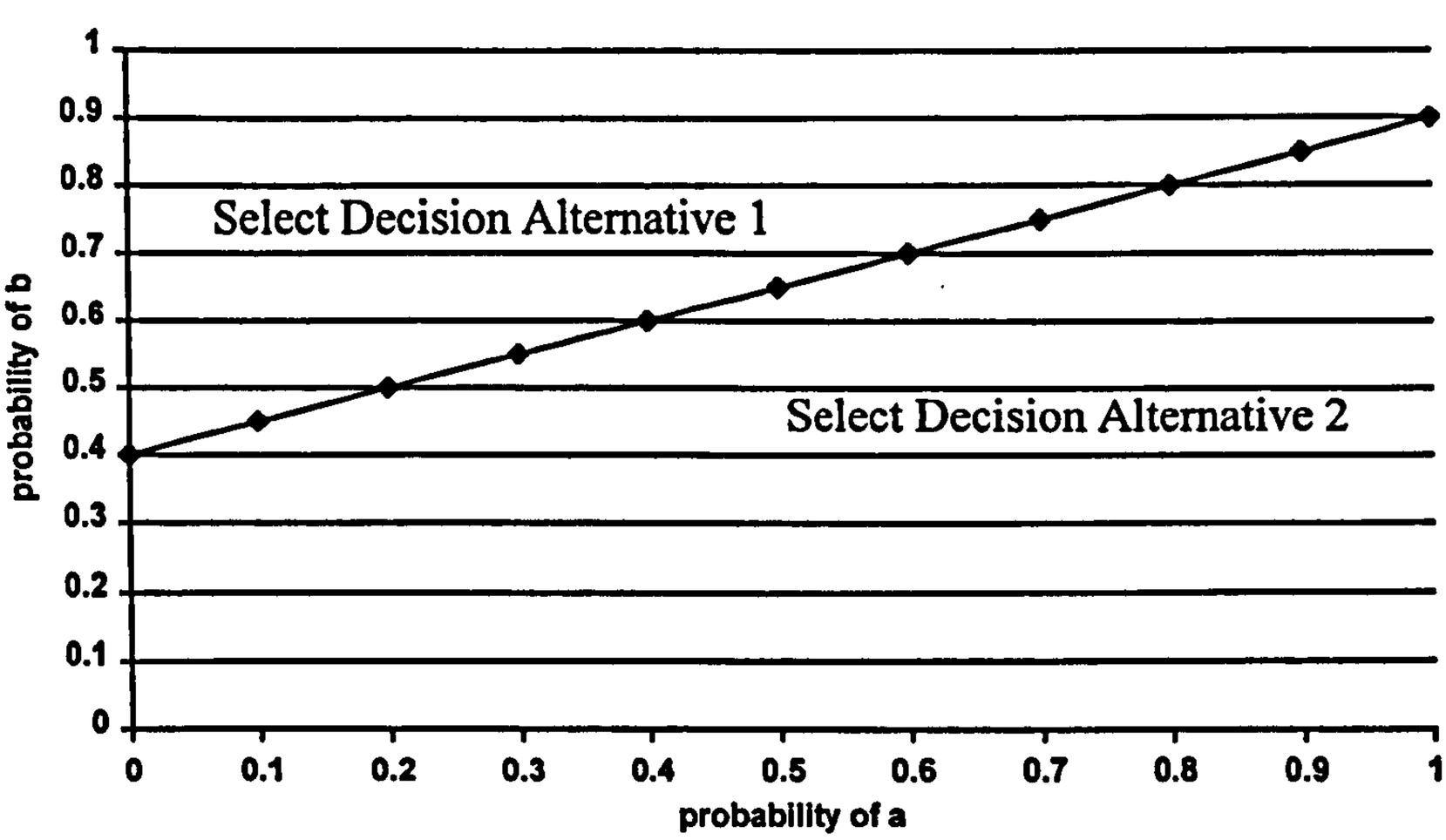


Figure 9 Example of Strategy-Region Graph

4.5.5.4 Alpha Value Sensitivity Analysis

On a more detailed level, it is possible to evaluate the uncertainty relative importance of each input variable in the structural reliability calculation. First and Second Order reliability analysis methods inherently provide "sensitivity factors" which express the relative importance of each basic random variable's uncertainty to the computed component failure probability [105]. This allows the decision-maker to identify the benefit of obtaining additional data to refine the most important uncertain variables.

4.5.5.5 Multi Dimensional Scaling

Multi-dimensional scaling can be used to determine the individual decision maker's preference diversity, their effect on the consensus weightings and the sensitivity of the final outcome to any conflicts. A map is produced showing the relative positions of a number of attributes based on the distance between each attribute pair. Using each decision makers' weights produced from interviews, it is possible to calculate the total distance between any two decision-makers. A map can then show each decision makers' relative position. The consensus weights can also be added to the map to investigate the existence of a true consensus rather than a purely mathematical one. Finally, the decision makers can be grouped using cluster analysis to identify possible reasons behind any clustering. This ensures all decision makers were interviewed consistently.

4.5.6 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 through evaluation to the selection of the best alternative according to the decision maker's specified criteria and preferences. A wide range of available decision analysis methods has been described and their limitations and strengths have been discussed.

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

4.5.6.1 Identify problem or opportunity

In structural asset management, someone other than the asset manager may notice either something amiss or a likely decision opportunity. The asset manager must initiate a detailed inquiry into the problem from many different viewpoints to ensure it is clearly understood. If this is not fulfilled here, confusion can occur later, when further details are defined. This is further magnified if more than one decision-maker is involved. The problem definition would evolve best through discussions with the stakeholders until a clearly defined problem is presented.

4.5.6.2 Identify Stakeholders in the decision

The existence of multiple stakeholders has a significant influence on the decision-making process. The objective of accounting for all appropriate stakeholders in a decision is to obtain ownership and commitment to the decision implementation by all.

Building group consensus in decision-making can be achieved through sharing, aggregating and comparing methods, involving negotiation, joint scoring systems and voting techniques. Each method is appropriate in different situations depending on the strength of stakeholders' feelings.

4.5.6.3 Identify viable alternatives

Structural asset management decisions are usually evaluation type problems. This means that it is necessary to identify all of the alternatives available. Of the techniques available for generating alternatives, the simpler methods such as attribute listing and brainstorming are the most appropriate in these applications as they involve little methodology for a potentially high output. Interactive software to support brainstorming makes the process less tedious for the decision-makers involved. The complete set of alternatives can then be reduced to a manageable size by removing alternatives that are infeasible, unacceptable in terms of stakeholder perception, or clearly inferior.

4.5.6.4 Formulate decision objectives and criteria

The decision criteria must be comprehensive and measurable representations of the decision-maker's objectives. They are used to describe the different alternatives. If the alternatives are known, then a "bottom-up" approach can be used to determine the decision criteria. The alternatives can be compared to identify their differences or their

weaknesses and strengths. These differences form the basis for developing decision criteria. It is important to identify minimum standards constraining the alternatives.

4.5.6.5 Structural Analysis

Decision matrices can model straightforward decisions under uncertainty although in structural asset management the decisions are unlikely to be this straightforward. Influence diagrams represent decision problems graphically and are particularly useful for the structuring phase of problem solving and for representing large or complex problems. Decision trees represent sequential decisions and allow the influence of future decision consequences to be traced back. Decision trees show more detail than influence diagrams and can, therefore, become too complex.

4.5.6.6 Uncertainty and probabilistic analysis

Hertz presented a form of Monte Carlo Simulation to rigorously account for uncertainty by defining subjective probabilities. Structural reliability methods aim to treat design and assessment uncertainties rationally. Probability distributions model the uncertain parameters to allow the component failure probability to be calculated. The component is acceptable if the computed reliability is higher than the specified target reliability. The individual reliability analysis results are then combined to calculate the total component reliability.

The failure probability can be calculated using numerical integration, Monte-Carlo simulation or FORM/SORM methods. Monte-Carlo simulation is computationally expensive if the failure probability is very small, as is typical of many structural components. FORM/SORM analyses approximate to the non-linear limit-state function, to efficiently compute the failure probability, and are now the most widely used methods. If a higher level, less detailed view of the problem is required, simplified risk scoring system can be used.

4.5.6.7 Utility/Value Analysis

There are two types of preferences to be considered in the decision analysis: utility and weighting. These 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.

4.5.6.8 Selection of "best" alternative

Several methods are available for selecting the best alternative based on scored and weighted attributes. In the analytic hierarchy process, the weighted attribute scores are summed for each alternative, which are then ranked according to their total weighted scores. The "best" option would be the one with the highest score.

Other methods available consider the individual attribute scores rather than the direct sum of the score. One of the most common is the Expected Value Principle, which uses informal preferences and risk calculations clearly communicated to decision-makers.

4.5.6.9 Sensitivity Analysis

Sensitivity analysis is an integral part of the decision process. It ensures that a decision does not treat a symptom rather than a cause. Sensitivity analysis of the problem structuring could identify a need to develop a more complete set, or detailed description, of possible outcomes. Sensitivity analysis can also help determine the important variables whose uncertainties would be best refined. Finally, sensitivity analysis can determine the diversity of individual decision makers' preferences, their effect on the consensus weightings and the sensitivity of the final outcome to any conflicts.

4.5.6.10 Final Remarks

This review has revealed significant opportunities for further work. For example, the development of utility functions is challenging when a detailed relationship between utility and each criterion is required. The prediction of failure consequences is also very difficult as actual failures are very rare and data is inevitably limited. The evaluation of distributions for each consequence utility is also very demanding. Further research is also needed to identify the best sensitivity analysis methods. At a higher level, interactions need to be developed between the separate theories to produce a holistic decision process to handle all the complexities and conflicts involved in structural asset management.

These methods have been discussed in the context of bridge management decision problems that involve significant uncertainties and the broad variety of strong stakeholder opinions. Decision analysis is expected to offer a rational and auditable method for combining all factors and opinions to arrive at the best decision for all parties. Work is still required to identify and apply the most appropriate decision tools to each stage of the decision process for risk-based structural asset management decisions.

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 and to identify a preferred course of action. This process, when applied carefully, will lead to better considered, justifiable and explicable decisions.

4.6 A Review of Decision Support Software

Modern computer systems and databases have provided new opportunities in decision-making. The need for information access and processing is a critical part of the decision-making process. Tools have only recently 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 decision problem structuring, probability and value elicitation and sensitivity analysis. These aid the decision maker in the problem formulation and evaluation. 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 and is a multi attribute decision support program based on Saaty's analytic hierarchy

process [100]. The structuring module provides a framework for collecting ideas (e.g. pros and cons of alternatives) and transforming them, by developing and organising criteria into an AHP model. This method is only suitable for conceptualising small problems and becomes cumbersome as the problems increase in size. The evaluation and choice module allows pair wise comparisons, solution synthesis, sensitivity analysis and report generation. In small problems, the criteria at each hierarchy level are pair wise compared, but this is impractical with larger problems. An alternative method is provided in which the alternatives are compared against a set of standards instead. This approach significantly reduces the number of comparisons that are required. The Inconsistency Ratio is calculated and recommendations for improved consistency are made, under user control. It is possible to enter quantitative criteria data directly (e.g. costs). Probabilities can also be input. Solution synthesis provides and graphically presents an overall score for each alternative. Sensitivity analysis uses several different graphical modes to consider the sensitivity to criteria priorities.

CRITERIUM DECISION PLUS implements two approaches to multi attribute decision-making. It uses both Saaty's analytical hierarchy process [100] and Edwards' Simple Multi Attribute Rating Technique (SMART) [109]. The software helps the user understand multi-criteria analysis and the effect of outcome uncertainty and preference on the decision options. A brainstorming module sets up complex models and converts them automatically into a hierarchy, which the decision-maker can modify. The software helps the decision-maker assign consistent relative importances to criteria (using numbers, bar graphs and words) and rates the alternatives against the criteria. Each alternative's weighted score indicates how well they meet the decision criteria. By graphically presenting the results, the decision-maker can analyse the decision for reasonableness, robustness and sensitivity to trade-offs. The decision-maker can also apply probability distributions to define uncertain data. The outcomes based on these uncertainties are overlaid on the results from a deterministic assessment to graphically represent the impact of uncertainty on the decision. Sensitivity analysis of the uncertainties identifies the most important uncertainties to reduce. This package is apparently as robust as EXPERT CHOICE and has the added advantage of being able to choose between SMART and AHP for evaluating importances.

Other packages allowing alternatives structuring and criteria weights definition through AHP and/or SMART are HIPRE3+, LOGICAL DECISIONS and ALIAHTHINK. However, these do not have the added benefit of uncertainty analysis.

Simplified decision software tools are available to allow decision problem definition through decision trees and influence diagrams, based on single attribute decision-making and the expected value criterion. Some packages have powerful uncertainty analysis tools such as ANALYTICA, CRYSTAL BALL, DEFINITIVE SCENARIO, NETICA and DECISION PRO. The tools based only on subjective probabilities and expected value criteria include PRECISIONTREE, DPL (Decision Programming Language) and DATA.

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 and DECISION EXPLORER. These use group brainstorming techniques to develop the model and voting techniques to 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 the benefit brought by these tools to decision-making, in terms of time saving, problem visualisation and consensus building, is clear.

4.7 Conclusions

In nearly every industry, many difficult and complex decisions about the industry's assets are made 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 will vary. However, one common factor within all these decisions is that they all involve risk.

Asset managers responsible for decision-making are required to justify the basis on which risks are managed. This review has already discussed the obstacles to doing this rationally. In some industries it is necessary to show that codes and standards have been applied appropriately. When codes and standards are met for at least one decision alternative, then it is possible to simplify the decision by removing all non-conforming alternatives. The choice between the remaining alternatives can then be based on cost and may also account for environmental effects, stakeholder values and company image. The risk-based decision process may not be essential, but may still be beneficial in these situations, to ensure that all important factors are taken into account

In cases where codes and standards do not apply, 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 becomes a much more significant driver in the decision problem, and the decision alternatives become more difficult to compare. The consequences of failure may also be more significant and may influence more stakeholders who would then have to be considered in the decision process. In addition to these complexities the 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 process, suggested here, is expected to be of most benefit.

The process has been designed to allow risks to be fully quantified and to allow other decision factors to be accounted for. Each decision factor can be assessed in its most convenient form without needing difficult judgements to be made to bring all factors to a common cost basis.

The greatest benefit of the risk-based decision process 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. A preferred course of action can be identified and agreed upon through discussion and consensus building leading to better considered and justifiable decisions.

After this review had been compiled and a substantial amount of the thesis work undertaken, a draft report was published by the UK Offshore Operators Association (UKOOA) [123]. The report outlines a framework to support decision-makers in identifying and evaluating appropriate decision factors in a given situation. The framework also helps establish the most appropriate basis for the decision depending on its context. The framework aims to help decision-makers determine the extent to which good practice, risk analysis and stakeholder values should be considered in each situation depending on a number of factors. These include 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 and the severity of economic implications. Based on these factors, decisions are categorised into three generic decision types. The framework then recommends thr processes to be adopted for each decision type. The UKOOA model is summarised in Figure 10 below:

The UKOOA report recommends that novel and challenging decision problems involving strong stakeholder views, major economic implications and significant risk and uncertainty should be addressed through combining engineering judgement, cost benefit analysis, quantitative risk assessment and evaluating company and societal values. This type of decision is most suited for solution with the support of the risk-based decision process proposed in this review. However, as stated previously, this does not necessarily mean that, the process will not aid decision-making in more apparently straightforward situations (as suggested by the UKOOA report).

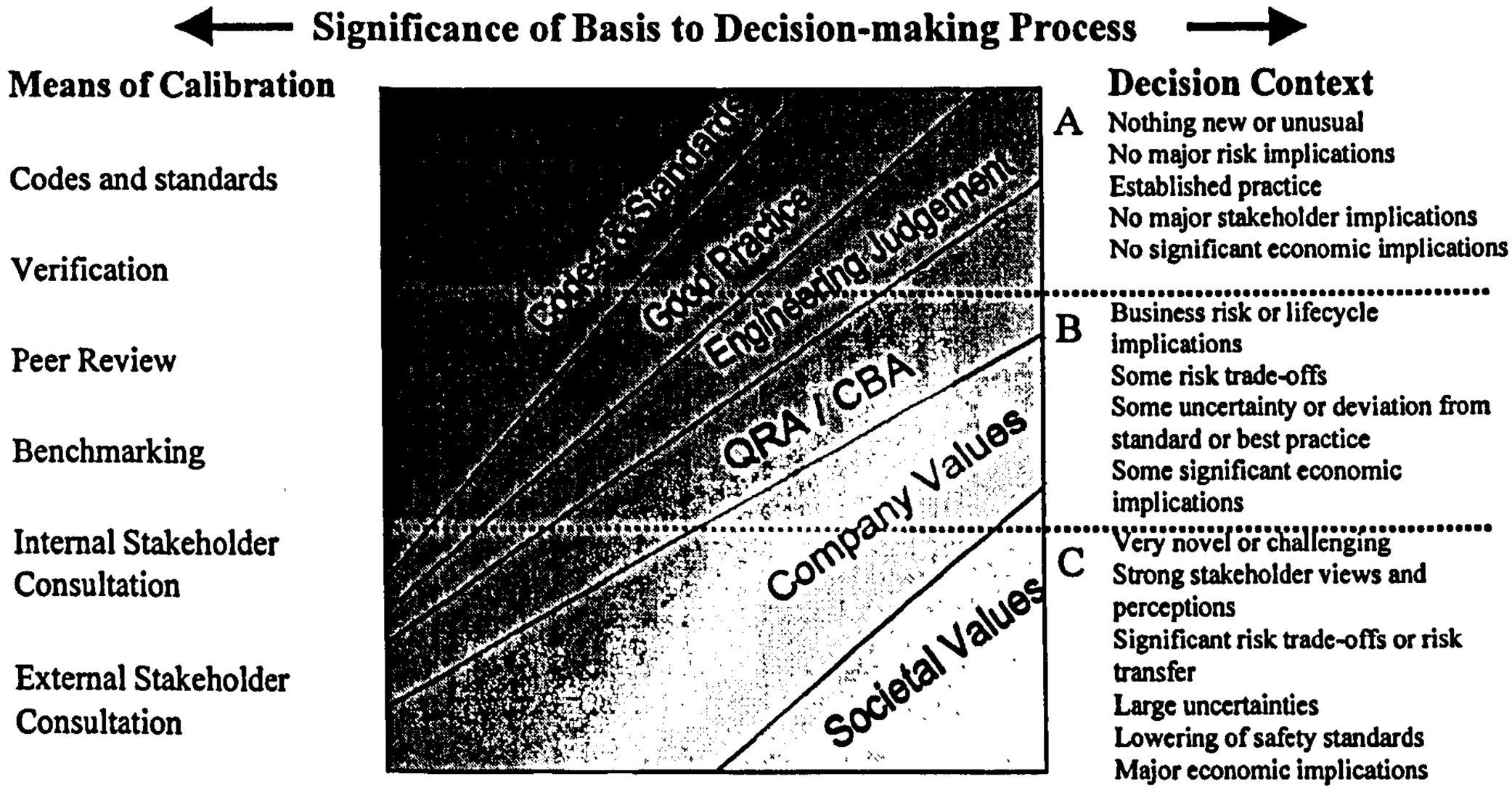


Figure 10: A decision support framework for decisions in the context of operations entirely within the goal-setting UK offshore regime, proposed by UKOOA [123]

It is expected that the decision process proposed out of this review will be a support to all risk-based structural asset management decision-making at different levels. At the simplest level, it can be used as a checklist to ensure that all factors are considered. At a more detailed level the different decision models can be adopted to evaluate and quantify all decision factors. The use of appropriate decision models for each decision situation would depend on many different factors such as:

- The level of detail required in the assessment of the problem
- The time-scale in which the decision has to be made
- The number and availability of alternative solution strategies
- The number of factors on which the decision is to be based
- The presence of strong and conflicting stakeholder influences
- The amount and level of uncertainty in the information available
- The probability of failure and the severity of failure consequences
- The degree of preferences and biases influencing the decision
- The level of optimality required in the solution
- The ability to revisit the decision following later inspection results

It is therefore important to develop a framework in which the available models can be considered in the context of the problem at the different stages of the decision-making.

A popular decision process was identified at the start of this literature review as the basis for a methodology. Comparison with characteristics of real life decision problems identified a number of gaps, including clearly identifying the decision problem, identifying and accounting for stakeholder influences, identifying decision criteria and objectives, identifying key decision parameters and allowing for re-valuation and model refinement.

The proposed risk based decision process has been enhanced with these improvements. It is now necessary to determine whether the use of the process does actually support real life decision-making and whether it accounts for all the important issues.

It is proposed that this risk based decision process be tested on a number of real life case studies that are representative of the range of decisions faced by asset managers in the life cycle of the assets, from conceptual design to end of life. The range of issues including stakeholder conflict, significant uncertainties and risks and multiple decision criteria should also influence the case studies. This risk based decision process will therefore form the basis for the remainder of this research.

5 RESEARCH METHOD

The research objectives were outlined in the introduction to this thesis in Section 2.4. The first objective, to identify tools and techniques that can be used to support decision-making was achieved in the literature review in the area of risk-based decision-making and its application to engineering decision situations. From this review, a clear research need was identified in the area of developing a risk-based decision methodology that could be applied to support engineering asset management decisions. This led to the development and proposal of a new, enhanced risk based decision process. This fulfils research objective 2, to develop a more comprehensive model to address the major issues of decision-making, within which the various tools and techniques can be applied. However, out of the vast number of individual decision models available, the problem is in identifying which models to use to help solve which problems. Having determined which models to use the second problem is in knowing how to apply them to the problems in a meaningful way that does not over simplify the problems. This leads on to the third objective, to apply the model and the appropriate tools and techniques to a range of real life decision problems.

Consistent with this objective, the following questions have been formulated to enable this objective to be met through empirically addressing them in each case study.

1. Do risk-based decision methods allow the problem to be fully explored and understood?
2. Do risk-based decision methods support the identification, evaluation and quantification of all significant risks?
3. Do risk-based decision methods support the identification and agreement of a preferred course of action?
4. Do risk-based decision methods make engineering decision-making easier?
5. Do risk-based decision methods help make more rational engineering decisions?
6. Do risk-based decision methods help make engineering decisions more auditable?
7. Do risk-based decision methods help build consensus and ownership in engineering decisions?
8. When is it appropriate to use risk-based decision methods in engineering decision-making?

In order to try to answer these questions, it was decided that the research should be as true to life as possible. Therefore, real life case studies were chosen as the basis for the majority of the research to allow a full understanding of the real life issues to be gained in the way the decision methods were applied, the benefits that were gained from them and the problems that were faced. The alternative approach would have been to carry out interviews or use questionnaires to investigate how decisions are made and whether practising engineers see a benefit in the methods. However, this approach would have allowed no experience of applying the methods, which was believed to be the important

issue and would have meant educating practising engineers in the methods available. The use of case studies allowed a hands-on approach to experiencing the difficulties encountered in real life decision-making such as a lack of data, short time-scales and stakeholder influences. It was believed that this would allow the maximum learning both on my part as a facilitator and consultant as well as on the part of the individual decision-makers and other stakeholders. Then, having exposed the decision-makers to risk-based decision methods for the first time, it would be clearer to identify the benefits that they gained from using them. A separate set of interviews was also used to compare how decisions are made in real life with the methods applied in this research.

The focus of the research however was the series of experimental case studies that allowed every dimension of decision-making with the support of risk-based decision models to be experienced.

The literature review showed how decision problems have frequently been modified to fit the decision model that is being used to solve them, often with unsatisfactory results, or have been carried out as purely academic exercises. Issues such as time-scales, stakeholder influences, amount of information, significance of the risks and availability of alternatives, however, are all factors that cannot be controlled by the decision-maker, but are dependent on the decision problem. The real benefit was therefore, expected to be gained from experimenting with the decision models to make them fit real life decision problems in a way that would bring benefit to the way the decision was made.

In order to learn the most about applying risk-based decision methods to real life engineering asset management problems a number of key criteria were identified that any suitable case study should fulfil. These are listed below:

1. There should be a number of stakeholders at least interested in, but preferably also influenced by, the decision, with different views and preferences for the different outcomes.
2. There should be a number of alternatives from which to choose, with initially no clear obvious choice.
3. There should be a number of criteria and objectives, preferably conflicting, influencing the selection of the best alternative.
4. There should be a need to identify and gather relevant information to support the decision process.
5. There should be significant risks resulting from the different alternatives, which can be quantified to a certain extent.

The case studies ideally would represent each of these above issues to varying degrees, to allow an appreciation of their effect on the decision-making process. The case studies should be taken from different fields of engineering to allow for variations in availability of data, structural models, codes and stakeholder perspectives. The case studies should be taken from different stages of the structure's life cycle again to allow

for variations in availability of data, structural models, decision significance and stakeholder perspectives.

Due to the real life, real time nature of the case studies they could not be "designed" to address these different issues as they arose out of business opportunities during the schedule of the research period. They were therefore dictated by the client's requirements in terms of level of detail of analysis, time-scale of the decision and stakeholder involvement. However, despite this external control, the four case studies that were selected did fit the above requirements and complemented each other to provide a broad overview of the research area. Furthermore, a change in sponsoring company half way through the research period opened up opportunities for case studies from different engineering fields.

In order to address the above research questions in each case study, the proposed decision process, shown in figure 4 was applied to each case study, from the outset of the decision problem and the benefit gained was evaluated. The methods of analysis adopted for each case study differed according to the availability of data, the importance of the decision, the time available for the decision, the influence of stakeholders and the time in the structure's life. Therefore, the case studies are described separately in the following chapters along with the lessons learnt and the benefits gained from using these methods.

As mentioned briefly above, a fifth case study was also undertaken, based on questionnaires and interviews, to consider how real decisions are normally made, within the sponsoring company, when they do not have the support of a risk-based decision process. A number of recent projects were identified and the key engineers and project managers involved in these projects were interviewed. These interviews explored the managers' experiences in decision-making, the problems they have faced and any methods they have adopted in the past to help them. In addition, the effect of good and bad decision-making on the overall project outcomes was investigated.

Having applied the risk based decision process to the different case studies the research needs to investigate whether any benefit has been gained, and if so the extent of the benefit above "natural" decision-making. This will mean that the fourth research objective, to analyse the effects of using this model and drawing conclusions on whether it works and any implications for decision-makers, can be met. This is achieved through a cross case analysis in the discussion section of this thesis.

The background to the five case studies is briefly introduced below, however, the full description of their evaluation, in terms of the decision process, is presented in the following five chapters.

5.1 CASE STUDY 1: Feasibility of Re-using Subsea Facilities in New Field Developments

An operating company was considering the development of an oil field in the UK sector of the central North Sea. Early development work investigated a number of field development options. The operator narrowed down their options to a single drill centre

with 6 production wells including 1 spare, 3 water injection wells including 1 spare and a possible gas injection well. It was still planned for the initial development to be tied back to a Floating Production, Storage and Offloading Vessel (FPSO) (phase 1), but with an option to tie back to another nearby development later (phase 2).

Independent of this development, the installation contractor was also supporting a second operating company in their evaluation of abandonment strategies for one of their fields. This field consists of two drill centres tied back to an FPSO. This field has been operating for less than 2 years and has proven to be uneconomic.

The installation contractor was therefore investigating the opportunity of combining the abandonment of the second field with the hook-up of its FPSO at the new field during the same mobilisation period up to one year earlier. This would provide the first operator with the opportunity of starting production on the new field one year earlier.

The concept of the single mobilisation depends on the resolution of a number of key issues, such as the ability to re-use equipment and or the ability to procure equipment within the relatively short time frame. In addition to this, there are a number of important related issues such as certification/verification, which need to be addressed.

To assist in their investigation the installation contractor asked Andrew Palmer and Associates to perform a study. This included the development of a field layout, an overall assessment of the feasibility, a study to investigate the cost benefit of reusing equipment and development of project schedules

The decisions that had to be made concerning the feasibility of re-using the abandoned facilities for Phase 1 (and possibly Phase 2) of the new field development were very complex and involved some degree of uncertainty. For example, the successful removal of the abandoned risers, without damage was uncertain. These decisions were also sequential in that one decision could not be made until the results of a previous decision were known.

The probability and consequences of unsuccessful removal or re-installation was, therefore, a key influence on the decision-making. This made the use of the risk-based decision process very attractive. However, the decision was being made very early on in the design process at a conceptual level, therefore only a simple, high level decision analysis was required. Therefore, decision trees were adopted as a useful tool for modelling the problem and expert opinion was used to provide the necessary information. Stakeholder preferences were not considered at this stage due to the conceptual nature of the decision.

The problem was addressed by forming a workgroup consisting of experienced installation engineers. Within this workgroup, a brainstorming session was initially carried out to identify all the alternatives available within these decisions. These then formed the starting point for constructing decision trees through group discussion and as a part of this structuring process to identify the different possible outcomes of each decision alternative. Carrying this out in a work group environment meant that a cross-fertilisation of ideas ensured that every consequence was considered. Finally, again as a

group, probabilities of each outcome and associated costs were put to each branch of each decision tree. Again, carrying this out as a group meant that the probabilities and costs were as objective as possible as they were under scrutiny from the remaining group and therefore had to be fully justified. This whole process was carried out in a whole day, which meant that all members of the group were fully attentive, interested and committed to the process through out the day and did not give chance for distractions. Following the work group session, the decision trees were formalised and evaluated to fully quantify each alternative and identify the best alternatives available.

This work took six weeks from being presented with the problem to having a solution to present to the client.

5.2 CASE STUDY 2: Developing a Maintenance Strategy for Viaduct Crossbeams

Around ten years ago, a routine inspection of the group of viaduct crossbeams under consideration revealed significant deterioration of the waterproofing of the expansion joints. This had allowed water, contaminated with de-icing salts, to seep into the concrete and the dissolved chlorides to ingress through the concrete to attack the steel reinforcement. It takes many years for the corrosion process to cause the capacity of the crossbeam to be significantly reduced. However, even at the time, the potential significance of the problem was understood. The engineers responsible for the management of the viaducts set out a plan for repair and maintenance to address the problem before it became too serious and the capacity of any of the viaducts was seriously compromised. However, the pressure on each year's budgets was so high that the requested funds were never fully supplied. The repair work fell behind schedule each year, allowing further deterioration to occur. Finally, the backlog was so significant and the integrity of the viaducts so uncertain that the maintenance agent asked for help to prioritise each crossbeam for repair and strengthening, in terms of minimising the overall risk.

The problem of prioritising viaduct crossbeams for strengthening involves quantitative assessments of many different factors. These include the capacity of a crossbeam, consequences of failure of a crossbeam, traffic disruption and strengthening costs as well as subjective judgements of other less well defined issues such as impacts on the local community of traffic restrictions on the viaducts. When such multiple criteria are used, certain "trade-offs" are required, as different viaducts would score better in terms of different criteria considered in isolation.

The procedures for calculating the deterioration and the strength of deteriorated reinforced concrete bridge components are not fully codified at present. The partial safety factors given in the codes do not take into account the additional uncertainties involved in the rate of deterioration and the strength of deteriorated components. Therefore, it is difficult to make rational decisions concerning the strengthening requirement for the crossbeams.

For this reason, the case study developed a methodology for the reliability analysis of the viaduct crossbeams taking into account all the significant sources of uncertainty in loading, strength and deterioration parameters. The methodology evaluates the probability of failure of a crossbeam for the limit-states of bending, shear and bond failure. The results of the reliability analysis were then used as a more rational basis on which to make the necessary repair and strengthening decisions.

The problem was addressed by initially holding a number of meetings with the maintenance agent representatives and the highways agency to determine the objectives of the decision problem. Due to the time schedule for this project, the focus of the work was on the risk assessment of the crossbeams (calculation of probability and consequence of failure). This was because establishing a better understanding of the reliability of the crossbeams was considered the most critical problem to give confidence (or otherwise) in the safety of the structures. The development of a decision strategy for selecting crossbeams for strengthening and identifying appropriate strengthening methods was to be addressed as a second phase. Despite the focus of this work on structural reliability calculations, the problem is still discussed in the format of the risk-based decision framework, as the structural reliability results inform the necessary decisions. The decision-making process is therefore discussed at a higher level.

This work took 15 months from being presented with the problem to the time my involvement ended as I moved on to a different sponsoring company. This involved formulating the problem, identifying and gathering necessary data, detailed evaluation of the information and development of the necessary models with which to assess the data. Finally, the calculation of the probability of failure for a number of different crossbeam types would allow a decision strategy to be formulated. However, as described in the associated chapter even at this point, the work was not completed.

5.3 CASE STUDY 3: Planning of Pipeline Repair and Replacement Schedules

The client for this work produces oil and associated gas from two large offshore fields. The fields have been in operation since soon after oil was first discovered in that area. Production fluids arrive at central processing platforms through a network of flowlines from unmanned satellite wells and from a companion field. Large diameter pipelines transport oil, gas and condensate for final treatment for export.

Corrosion has occurred in the production and injection water pipeline networks and the transmission pipelines. The client prefers to avoid leaks by proactive repair or replacement of corroded pipelines. We were requested to perform a Remnant Life Assessment (RLA) study of the field's Main Oil Pipelines including the development of Remnant Life Prediction software. This was then to be used to optimise the extent and timing of repair or replacement for each pipeline. The scope of work incorporated two Main Oil lines of 30" diameter.

The repair/replace decision problem addressed in this work is based on the predicted condition and hence integrity of the pipelines, based on a review of a number of surveys undertaken for the client over the last ten years. The quantitative results presented are based on wall thickness measurements obtained through two internal intelligent pig inspection surveys. The pig inspections were carried out in 29 and 32 years after commissioning using a magnetic flux pig and an ultrasonic inspection tool, respectively. In addition to the intelligent pigging inspections, a number of external ultrasonic inspections had also been carried out. These were also accounted for.

The two sets of intelligent pig results had been obtained using significantly different instruments. This means that the accuracy of the measurements obtained during the surveys is also significantly different. Because of this, a major obstacle in the assessment of the survey data is the reconciliation of the two sets of findings. It was therefore necessary to account for the uncertainties in the measurements to provide a realistic and rational basis for the repair/replace decisions to be made. This was done using probabilistic techniques, described later.

This case study presents a methodology for the risk-based remnant life assessment of corroding pipelines. The methodology accounts for the uncertainty in the deterioration parameters that dominate the problem (uncertainties in loading and resistance parameters were not accounted for). This allowed the probability distribution of the failure date to be evaluated for the pipeline for the limit states of through wall corrosion and rupture.

The problem was addressed by initially holding a number of meetings with the quality assurance department, responsible for ensuring the safety and operability of the pipelines, to determine the objectives of the decision problem. From these meetings, the conflicting views the two different shareholder groups became apparent. It was therefore decided that since the one agreed objective between the shareholders was to ensure absolute safety in the pipelines, the focus of the work should initially be a risk assessment of the pipelines in question. Since the dispute was on whether the pipelines should be repaired or replaced, a reliability based remnant life assessment was carried out, to help establish the cost benefit of repairs for the remaining life versus a full replacement. This provided a better understanding of the key issues involved. Despite the focus of this work on reliability calculations, the problem is still discussed in the format of the risk-based decision framework, as the structural reliability analysis informs the necessary decisions. The results of the risk-based remnant life analysis were therefore used as a more rational basis on which to make the necessary repair or replacement decisions. This allowed the focus of the decision to be placed on the most important factors and allowed the less important factors, which were viewed in conflicting ways by the stakeholders, to be discounted. This decision-making process is discussed at a higher level in the write-up.

This work took four months from being presented with the problem to presenting a solution to the client. This involved formulating the problem, identifying and gathering necessary data, detailed evaluation of the information and development of the necessary

models with which to assess the data. Finally, the calculation of the probability distribution for the pipeline remnant life allowed a solution to be identified and recommended.

5.4 CASE STUDY 4: Prioritisation of Bridge Strengthening Works

A consortium of bridge engineers from every London borough was faced with the problem of selecting the most important bridges, which had failed assessment, to be strengthened. Due to the very tight limits on budgets, only a small selection of those bridges requiring strengthening could be put forward for funding from the next year's budgets. We were commissioned with the task of rationally prioritising all of the bridges in the London area, to identify those in most urgent need of strengthening.

Significant uncertainties were involved in this problem (such as further deterioration of the bridges, excessive loading on the bridges and their current capacity). In addition, the different stakeholders held a broad variety of strong opinions (such as the Governors of London, the borough councils, local businesses and frequent users of the bridges). It was therefore felt that decision analysis could offer a rational and auditable method for combining all factors and opinions to arrive at the best decision for all parties.

The problem of prioritising bridge strengthening works involves quantitative assessments from bridge engineers concerning issues such as safety of the bridge, traffic disruption and strengthening costs. Subjective judgements of other less well-defined influences are also involved, such as impacts on the local community and the cost savings associated with combining works with upgrading work.

Certain trade-offs were required to select the "best" projects as different projects score better in terms of different issues. For example, one project may strengthen a bridge to a high level of safety but be very expensive, while another project may give only a small strength advantage but at very little cost.

This case study therefore, outlines the process that was carried out to determine the main factors considered important in the prioritisation of bridge strengthening works, and the relative importance of those factors. The results of this process are also presented to show how a consensus was achieved for the weightings of factors used to determine an overall "bridge priority index".

Due to the time schedule for this project, (the client had only a couple of months before this year's submissions for funding had to be completed), certain simplifications were imposed by the client:

- It was not at all feasible for all the bridges failing assessment to be subjected to a full structural reliability assessment; therefore, a simplified risk scoring system was used.
- The client requested that the bridges be prioritised on a current year basis. So that those bridges selected for strengthening this year would be removed from the list the following year.

- Representatives of four borough councils only were interviewed (borough bridge engineers and council representatives) to gain an idea of stakeholder views.

The problem was therefore addressed by first holding meetings with representatives of the consortium of engineers. This allowed the objectives of the decision to be identified and the types of stakeholders to be considered were discussed. The main decision criteria were then identified in a combination of brainstorming with the consortium representatives and reviewing previous related work. Interviews were then set up with a number of borough representatives, to allow the stakeholder views to be identified and the criteria preferences to be quantified. From these interview results consensus weightings were calculated. To ensure full stakeholder involvement, consensus and ownership of the final solution, intermediate results were communicated back to the interviewees and the consortium representatives at several stages. The information to support each alternative was then gathered through questionnaires sent out to every borough. The weighted decision criteria were applied to the information provided for each alternative, to allow a full ranking of the alternatives to be carried out. This was again presented to the consortium representatives who then presented it to all the borough representatives. This detailed communication meant that a full consensus was achieved throughout the stakeholders, which also supported the implementation of the final decision.

This work took seven months from being presented with the problem to presenting a solution to the client. This involved formulating the problem, identifying necessary data, developing a suitable interview technique for gathering the data, setting up and carrying out the interviews. It also involved detailed evaluation of the information gathered and the development of the necessary prioritisation models with which to assess the data gathered from the questionnaires. Finally, the prioritised list of alternatives was presented to the client for their approval.

5.5 CASE STUDY 5: Review of Risk-based Decision-making in Andrew Palmer and Associates

The process of field development involves several stages from the identification of a potential field through to delivery of first oil/gas. Currently at APA, preliminary engineering design starts after the high value field development (concept selection) decisions have been made. Decisions such as the type of field development, the need for a pipeline for product export and sometimes even the operating conditions of the pipeline have already been determined by the operator before they commission APA with the task of designing the pipelines. Therefore APA is left with the lower value, lower complexity decisions in preliminary and detailed pipeline design.

The earlier decisions made by the operator and the selected contract strategy can cause severe restrictions on the way design decisions are made by APA, causing APA to produce, at times, sub-optimal designs.

APA is faced with a number of preliminary engineering design decisions. These typically include the routing of the pipeline, the diameter and wall thickness of the line

pipe, the dimensions and locations of spools and crossings, types of valves and pigging facilities, methods for protecting the spools and valves, pipeline coatings and other corrosion inhibitors.

These decisions are not necessarily influenced by a large number of external stakeholders, neither are they dependent on a large number of factors. They are however, dependent on a few important and often conflicting factors, such as safety, durability, reparability, cost of installation, operation, maintenance and decommissioning, etc. They also are made under significant uncertainty such as uncertainty in the cost and in the inherent risk of each alternative. Most importantly, the decision has to be auditable for governing and regulatory bodies. Risk-based decision-making could help to fulfil these requirements.

A number of recent conceptual and preliminary engineering design projects were identified and reviewed in detail to establish the types of decisions that APA generally make in a conceptual and preliminary engineering design project. Also identified were the decisions that APA did not make, which were made already by the contractor or the operator. For every key decision, an indication of the main decision-makers, the important decision criteria and any constraints were identified.

A selection of senior engineers and managers within APA were then interviewed about the way they make decisions in conceptual and preliminary engineering design projects. The specific design projects that have been identified were explored in depth with the project managers and lead engineers that worked on these projects. In addition, project managers and senior engineers were asked more generally on the usual approach to conceptual and preliminary, engineering design decision-making and the types of decisions usually encountered. The results of these interviews were then assessed in detail and collated to build up a full picture of the problem encountered in unsupported decision-making and the consequences of these not being fully evaluated.

5.6 Summary of the Case Studies

The four real-life case studies were therefore selected to represent the broadest range of asset management decisions as possible in terms of a number of factors including:

- The time in the structures life cycle, for example the design stage, the operational stage and the decommissioning stage.
- The amount of data available to support risk analysis, for example subjective expert opinion, deterministic approximations or probabilistic distribution.
- The influence of stakeholders, considering for example, a negligible influence (where there is interest but very minimal influence); a noticeable influence, where different groups of people have a say in the final decision but also share similar goals and a significant influence where different groups of people have a say in the final decision but have conflicting goals.
- The time available to make the decision. For example, the difference between having less than two months and more than a year to produce a solution to the

decision has a significant influence on the level of detail with which the analysis can be carried out.

- The number of alternatives available. For example, the difference between choosing from two or three alternatives will require a different level of analysis to a decision between a vast number of alternatives.
- The number of decision criteria. For example, the difference between making a decision based on one or two decision criteria and making a decision based on multiple, conflicting criteria.
- The field of engineering. For example the difference between decision-making in the oil and gas industry and in the transportation industry.

Each level of each of the above characteristics is represented by at least one of the case studies, thereby ensuring that a broad variety of decision types were investigated in the research programme. The following table shows how the required variety was achieved between the four case studies.

		Case Study 1	Case Study 2	Case Study 3	Case Study 4
Life cycle time	Design	✓			
	Operation		✓	✓	✓
	Decommission	✓			
Amount of data	Expert judgement	✓			
	Deterministic				✓
	Probabilistic		✓	✓	
Stakeholder influence	Negligible	✓			
	Noticeable		✓	✓	
	Significant				✓
Time to make decision	T < 2 months	✓			
	2 mths< T < 9 mths			✓	✓
	9 months < T		✓		
Number of alternatives	N < 5			✓	
	5 < N < 20	✓			
	20 < N		✓		✓
Number of criteria	Expected Cost only	✓			
	Expected Cost and Safety		✓	✓	
	Multiple Criteria				✓
Field of Engineering	Bridge Engineering		✓		✓
	Pipeline Engineering	✓		✓	

Table 5 Summary of the four real-life case studies adopted for the research

6 CASE STUDY 1

FEASIBILITY OF RE-USING SUBSEA FACILITIES IN NEW FIELD DEVELOPMENTS

6.1 Problem Definition

6.1.1 Identify problem or opportunity

The decision problem evaluated in this case study was identified by an installation contractor who was consecutively investigating the development options of one operator's new field and the decommissioning options of a second operator's abandoned field.

The installation contractor identified the opportunity of combining the abandonment of the abandoned field with the hook-up of its disused FPSO at the new field during the same mobilisation. This would provide operator of the new field with the opportunity of starting production one year earlier.

The concept of the single mobilisation depends on the resolution of a number of key issues, such as the ability to re-use equipment and or the ability to procure equipment within the relatively short time frame. In addition to this, there are a number of important related issues such as certification/verification, which need to be addressed.

Andrew Palmer and Associates were asked to perform a study, which included the development of a field layout, an overall assessment of the feasibility, a study to investigate the cost benefit of reusing equipment and development of project schedules.

These decisions also involve multiple stakeholder views, for example, operators prefer to reuse the maximum amount of infrastructure, while contractors and designers will only gain revenue if new infrastructure is designed.

The objective of this risk-based decision analysis was to evaluate, as rationally as possible, the alternative options available for the reuse, abandonment or disposal of the different redundant facilities. Where necessary, the comparative costs of purchasing new have also been considered.

6.1.2 Identify Stakeholders in the decision

A number of stakeholders were interested in and or influenced by these decisions. These included:

- the abandoned field operator who was looking for some compensation;
- the new field operator who wanted to minimise installation costs and lead times;
- the installation contractor and designers who would benefit from the design and procurement of new facilities;
- environmental and legislative bodies who were keen to minimise risks.

However, the decision was taken at very a conceptual level. The objective was to investigate the feasibility and cost effectiveness of the alternatives, rather than building

consensus between stakeholders, at this stage. Therefore, the different stakeholder preferences were not taken into account at this stage.

6.1.3 Identify viable alternatives

Five sub-decisions were considered, to decide on whether to re-use or abandon and buy new for each type of facility. The available alternatives for each sub-decision are summarised in the table below:

	Number Available	Number Required	Decommissioning Requirements	Decision Alternatives
Production and Water injection risers	4	3	Must be removed	Remove & Reuse or Remove, Dispose and buy new
Gas Lift Risers	2	1	Must be removed	Remove & Reuse or Remove, Dispose and buy new
Dynamic Umbilicals	2	1	Must be removed	Remove & Reuse or Remove, Dispose and buy new
Flowline Umbilicals	2	1	Can be abandoned	Remove 1 or 2 and reuse or abandon and buy new
Structures	1	1	Must be removed	Remove & Reuse or Remove, Dispose and buy new

Table 6: Summary of the decision alternatives for each sub decision

6.1.4 Formulate decision objectives and criteria

Each decision was modelled in the context of minimising (in simplistic terms) the expected whole life cost of the alternatives available for the new field development. The whole life cost assessment was simplistic in that the only post installation cost considered was the cost of replacing the risers if they failed during operation as a result of the decision to reuse the abandoned risers. The risks common to both alternatives were not considered.

6.2 Structural Analysis

The structuring process supports the decision-maker in the identification of all possible alternatives and all possible outcomes. 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 straightforward, the decision tree can also be used to help solve the problem. 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 to allow the best decision to be chosen.

A complex decision tree was generated for each sub-decision and considered the choice between the proposed alternatives described previously. For the removal options, the chance of successfully removing each item from the disused installation was considered (successful removal included minor damage that could be easily repaired offshore). Then for each alternative, the chance of successfully installing each item into the new

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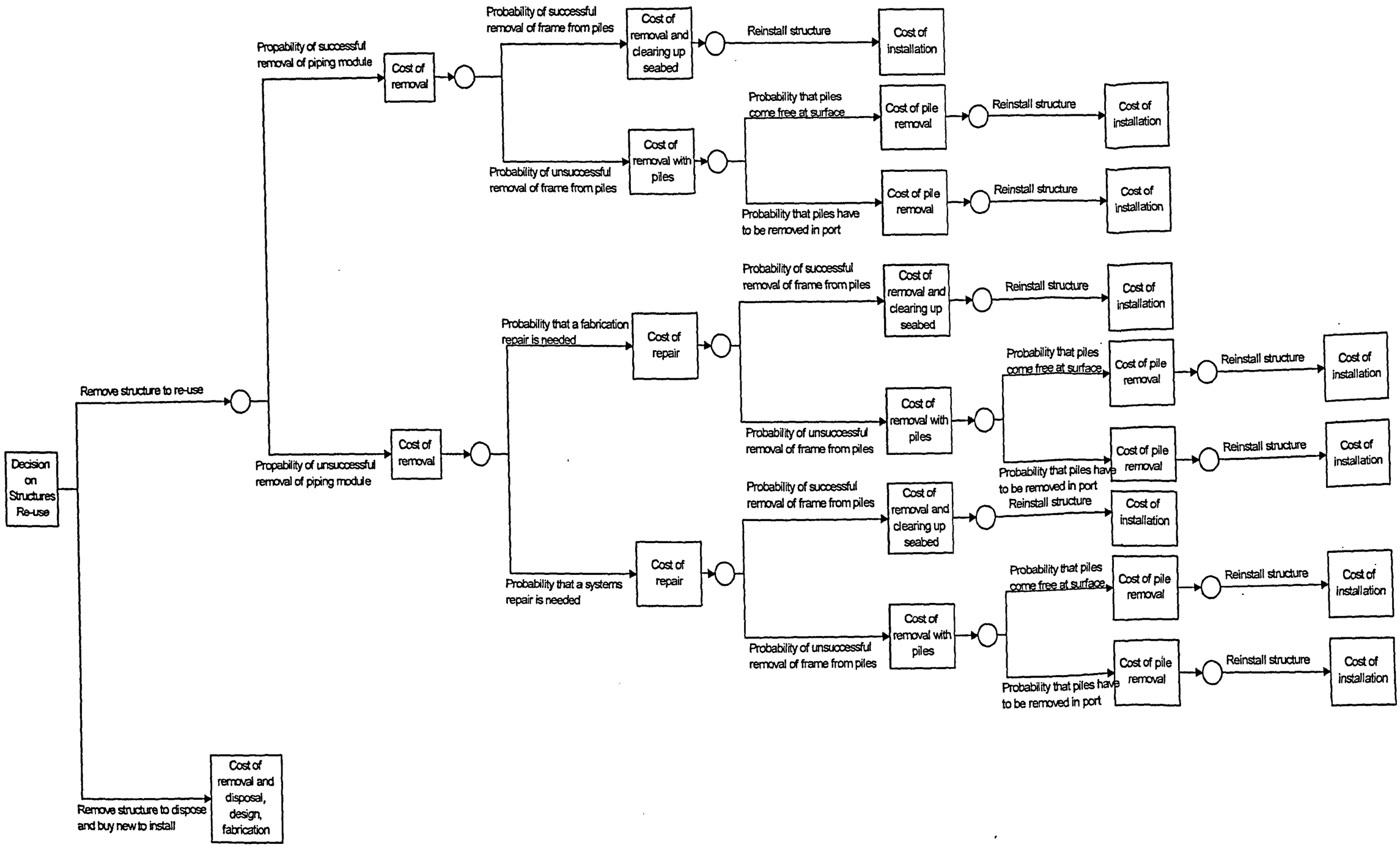


Figure 11: Decision tree of the evaluation of alternatives for the reuse of the structures

field was considered followed by the chance of successful tie-in and the chance of each item surviving the design life. An example decision tree is shown in Figure 11. The detailed decision trees for each decision problem are shown in Appendix 2.

6.3 Uncertainty and Probabilistic Analysis

Engineers experienced in the removal and installation of subsea infrastructure subjectively determined the probability of each event. These were "first pass" estimates which could be refined later with more accurate information if it was considered worthwhile. The following outlines some of the assumptions made in the evaluations.

- The sum of the probability of all possible outcomes of an event equals 1.
- The probability of successful tie-in was not affected by the item being reused or new.
- The probability of successful tie in of the flowline umbilicals/structures was set to 1.
- The probability of all items surviving phase 1 (i.e. the short term tie-back to FPSO) was set to 1.
- The probability of the flowline umbilicals/structures surviving phase 2 (i.e. the longer term tie back to another pipeline) was set to 1.

The following tables list the probability values of used for each decision problem:

Probability of successfully removing 4 risers	0.9
Probability of successfully removing only 3 risers	0.07
Probability of successfully removing only 2 risers	0.025
Probability of successfully removing only 1 riser	0.004
Probability of successfully removing 0 risers	0.001
Probability of midline damage to riser in removal	0.3
Probability of end damage to riser in removal	0.7
Probability of installing 3 out of 4 risers	0.95
Probability of installing 2 out of 4 risers	0.03
Probability of installing 1 out of 4 risers	0.015
Probability of installing 0 out of 4 risers	0.005
Probability of installing 3 out of 3 risers	0.92
Probability of installing 2 out of 3 risers	0.06
Probability of installing 1 out of 3 risers	0.015
Probability of installing 0 out of 3 risers	0.005
Probability of end damage to riser in installation	0.6
Probability of midline damage to riser in installation	0.4
Probability of successful tie-in	0.98
Probability of unsuccessful tie-in	0.02
Probability of surviving phase 2	0.99
Probability of surviving phase 1 only	0.01

Table 7 List of probabilities used as inputs to evaluate the decision of whether to re-use the production and water injection risers or not.

Probability of successfully removing 2 risers	0.95
Probability of successfully removing only 1 riser	0.045
Probability of successfully removing 0 risers	0.005
Probability of midline damage to riser in removal	0.3
Probability of end damage to riser in removal	0.7
Probability of installing 1 out of 2 risers	0.99
Probability of installing 0 out of 2 risers	0.001
Probability of installing 1 out of 1 riser	0.97
Probability of installing 0 out of 1 riser	0.03
Probability of end damage to riser in installation	0.6
Probability of midline damage to riser in installation	0.4
Probability of successful tie-in	0.98
Probability of unsuccessful tie-in	0.02
Probability of surviving phase 2	0.99
Probability of surviving phase 1 only	0.01

Table 8 List of probabilities used as inputs to evaluate the decision of whether to re-use the gas injection risers or not.

Probability of successfully removing 2 umbilicals	0.95
Probability of successfully removing only 1 umbilical	0.045
Probability of successfully removing 0 umbilicals	0.005
Probability of midline damage to riser in removal	0.2
Probability of end damage to riser in removal	0.8
Probability of installing 1 out of 2 umbilicals	0.99
Probability of installing 0 out of 2 umbilicals	0.001
Probability of installing 1 out of 1 umbilical	0.97
Probability of installing 0 out of 1 umbilical	0.03
Probability of end damage to riser in installation	0.8
Probability of midline damage to riser in installation	0.2
Probability of successful tie-in	0.98
Probability of unsuccessful tie-in	0.02
Probability of surviving phase 2	0.99
Probability of surviving phase 1 only	0.01

Table 9 List of probabilities used as inputs to evaluate the decision of whether to re-use the dynamic umbilicals or not.

Probability of successfully removing 1 out of 1 umbilical	0.9
Probability of successfully removing 0 out of 1 umbilical	0.1
Probability of successfully removing 2 out of 2 umbilicals	0.81
Probability of successfully removing only 1 out of 2 umbilicals	0.18
Probability of successfully removing 0 out of 2 umbilicals	0.01
Probability of installing 1st umbilical	0.96
Probability of not installing 1st umbilical	0.04
Probability of installing 2nd umbilical	0.98
Probability of not installing 2nd umbilical	0.02
Probability of installing 3rd umbilical	1

Table 10 List of probabilities used as inputs to evaluate the decision of whether to re-use the flowline umbilicals or not.

Probability of successfully removing piping module	0.97
Probability of unsuccessfully removing piping module	0.03
Probability of minor repairs to piping module	0.85
Probability of major repairs to piping module	0.15
Probability of successfully removing structure from piles	0.8
Probability of unsuccessfully removing structure from piles	0.2
Probability of piles freeing on surface	0.7
Probability of piles being stuck on surface	0.3

Table 11 List of probabilities used as inputs to evaluate the decision of whether to re-use the structures or not.

6.4 Utility/Value Analysis

The value of each option was determined on a purely cost basis. The costs were evaluated subjectively based on the experience of engineers in design, installation and removal of subsea infrastructure. Again, these were "first pass" estimates which could be refined and updated later with more accurate information if it was considered worthwhile. The following outlines some of the assumptions made in the evaluations.

For each action, for each option, the costs considered

- a mobilisation cost,
- the number of vessel days required to carry out the operation
- the day rate of the type of vessel that would have to be used,
- the cost of materials used (e.g. for repair work or for new purchases)
- transportation costs associated with the acquisition of materials

- the cost of disposing of redundant items (salvage value was accounted for where appropriate)
- the cost of the consequences of major schedule delays, based on the interest on investment.

Considering specific costing assumptions:

- The costs of removal also allowed for costs of minor offshore repair work and any necessary testing.
- The cost of removing the flowline umbilicals also included the costs of deburial.
- A moderately damaged riser or flowline was taken as having suffered from end damage, therefore the cost of repair was taken to be the cost of returning to port to re-terminate the line. A severely damaged riser or flowline was taken as having suffered mid-line damage; therefore, the cost of repair was taken to be the cost of returning to port and replacing the line, with the consequential costs of schedule delays.
- A riser damaged during tie-in was assumed to suffer moderate damage as defined previously and therefore requires removal and re-terminating. These costs were therefore included here.
- Unsuccessful recovery of the piping modules was considered to result in fabrication damage (requiring structural repair of flanges etc.) or system damage resulting in the need for major repairs to valves, controls, etc. The associated schedule delay consequences were, therefore included.
- Unsuccessful removal of the structure frames was assumed to result in two levels of failure. 1) Failure to remove from the piles on the seabed requiring removal on the surface. 2) Failure to remove from the piles on the surface requiring specialist equipment in port. The consequential costs of vessel time, and schedule delays were therefore accounted for.

The following tables list the input values of costs that were used for each decision problem:

Production & Water Injection Risers	Total cost	Vessel days	Vessel rate/day	Materials	Transport	Mobilisation	Disposal	Delay cost/wk	Delay (wks)
Cost to remove 4 risers	1500000	12	100000	0	0	300000	0	28500	0
Cost of 3 new risers	2690000	12	100000	1000000	50000	300000	140000	28500	0
Cost to repair 1 riser after damage	650000	6	100000	50000	0	0	0	15000	0
Cost to repair 2 risers after damage	800000	7	100000	100000	0	0	0	28500	0
Cost to repair 3 risers after damage	950000	8	100000	150000	0	0	0	28500	0
Cost to replace 1 riser	1625000	5	100000	350000	50000	300000	35000	15000	26
Cost to replace 2 risers	2561000	7	100000	700000	50000	300000	70000	28500	26
Cost to replace 3 risers	3096000	9	100000	1000000	50000	300000	105000	28500	26
Cost to install 3 risers	1000000	10	100000	0	0	0	0	28500	0
Cost to repair riser after wrong tie-in	1407000	10	100000	50000	0	300000	0	28500	2
Cost to replace riser in operation	1925000	10	100000	150000	50000	300000	35000	15000	26

Table 12 List of costs used as inputs to evaluate whether to re-use the production and water injection risers or not.

Gas Lift Risers	Total cost	Vessel days	Vessel rate/day	Materials	Transport	Mobilisation	Disposal	Delay cost/wk	Delay (wks)
Cost to remove 2 risers	900000	6	100000	0	0	300000	0	28500	0
Cost of 1 new riser	1220000	6	100000	200000	50000	300000	70000	28500	0
Cost to repair 1 riser after damage	650000	6	100000	50000	0	0	0	28500	0
Cost to repair 2 risers after damage	800000	7	100000	100000	0	0	0	28500	0
Cost to replace 1 riser	1826000	5	100000	200000	50000	300000	35000	28500	26
Cost to replace 2 risers	2261000	7	100000	400000	50000	300000	70000	28500	26
Cost to install 2 risers	400000	4	100000	0	0	0	0	28500	0
Cost to repair riser after wrong tie-in	1407000	10	100000	50000	0	300000	0	28500	2
Cost to replace riser in operation	2226000	10	100000	100000	50000	300000	35000	28500	26

Table 13 List of costs used as inputs to evaluate whether to re-use the gas injection risers or not.

Dynamic Umbilicals	Total cost	Vessel days	Vessel rate/day	Materials	Transport	Mobilisation	Disposal	Delay cost/wk	Delay (wks)
Cost to remove 2 umbilicals	900000	6	100000	0	0	300000	0	28500	0
Cost of 1 new umbilical	1020100	6	100000	100	50000	300000	70000	28500	0
Cost to repair 1 umbilical after damage	650000	6	100000	50000	0	0	0	28500	0
Cost to repair 2 umbilicals after damage	800000	7	100000	100000	0	0	0	28500	0
Cost to replace 1 umbilical	1726000	5	100000	100000	50000	300000	35000	28500	26
Cost to replace 2 umbilicals	2061000	7	100000	200000	50000	300000	70000	28500	26
Cost to install 2 umbilicals	400000	4	100000	0	0	0	0	28500	0
Cost to repair umbilical after wrong tie-in	1407000	10	100000	50000	0	300000	0	28500	2
Cost to replace umbilical in operation	2226000	10	100000	100000	50000	300000	35000	28500	26

Table 14 List of costs used as inputs to evaluate the decision of whether to re-use the dynamic umbilicals or not.

Flowline Umbilicals	Total cost	Vessel days	Vessel rate/day	Materials	Transport	Mobilisation	Disposal	Delay cost/wk	Delay (wks)
Cost to remove 1 umbilical	650000	6	75000	0	0	200000	0	28500	0
Cost of 1 new umbilical	350000	0	75000	100000	50000	200000	0	28500	0
Cost to remove 2 umbilicals	800000	8	75000	0	0	200000	0	28500	0
Cost to repair 1 umbilical after damage	500000	6	75000	50000	0	0	0	28500	0
Cost to replace 1 umbilical with old	685000	6	75000	0	0	200000	35000	28500	0
Cost to replace umbilicals with old	1135000	12	75000	0	0	200000	35000	28500	0
Cost to replace umbilicals with new	2026000	12	75000	100000	50000	200000	35000	28500	26
Cost to install 1 umbilical	225000	3	75000	0	0	0	0	28500	0

Table 15 List of costs used as inputs to evaluate the decision of whether to re-use the flowline umbilicals or not.

Structures	Total cost	Vessel days	Vessel rate/day	Materials	Transport	Mobilisation	Disposal	Delay cost/wk	Delay (wks)
Cost to remove piping module	625000	5	75000	0	50000	200000	0	28500	0
Cost to remove frame 1st time	75000	1	75000	0	0	0	0	28500	0
Cost to buy new	3100000	18	75000	1500000	50000	200000	0	28500	0
Cost to clear seabed	75000	1	75000	0	0	0	0	28500	0
Cost to remove structure from piles on surface	450000	6	75000	0	0	0	0	28500	0
Cost to repair structure on shore	300000	4	75000	0	0	0	0	28500	0
Cost of minor repairs to piping module	557000	6	75000	50000	0	0	0	28500	2
Cost of major repairs to piping module	1291000	6	75000	100000	0	0	0	28500	26
Cost to install	525000	7	75000	0	0	0	0	28500	0

Table 16 List of costs used as inputs to evaluate the decision of whether to re-use the structures or not.

6.5 Selection of "Best" Alternative

The probabilities and costs for each action were combined within the decision trees to give a total expected cost of each decision alternative. This can then be used as the basis for choosing between alternatives. The results of the decision tree analyses are presented below:

Decision	Remove all 4 production & water injection risers & reuse 3	Remove all 4 production & water injection risers and buy 3 new
Expected Cost	**£2 660 213**	**£5 315 123**

Table 17: Results for Reusing the Production and Water Injection Risers

Decision	Remove both Gas Lift Risers and reuse 1	Remove both Gas Lift Risers and buy 1 new
Expected Cost	**£1 375 804**	**£2 595 545**

Table 18: Results for the Reuse of the Gas Lift Risers

Decision	Remove both Dynamic Umbilicals and reuse 1	Remove both Dynamic Umbilicals and buy 1 new
Expected Cost	**£1 378 207**	**£2 391 291**

Table 19: Results for the Reuse of the Dynamic Umbilicals

Decision	Remove one Flowline Umbilical to reuse	Remove both Flowline Umbilicals and reuse 1	Leave both Flowline Umbilicals and buy 1 new
Expected Cost	£1 023 178	£1 279 292	£ 636 281

Table 20: Results for the Reuse of the Flowline Umbilicals

Decision	Remove each structure to reuse	Buy new structures
Expected Cost	**£2 505 475**	**£3 100 000**

Table 21: Results for the Reuse of the Structures

From this analysis, it can be seen that the risers and the dynamic umbilicals should be removed and reused, but that the flowline umbilicals should be left on the seabed. The choice between re-using the structures or not is quite close and therefore would definitely benefit from some sensitivity studies on costs and risks.

6.6 Sensitivity Analysis

APA engineers have evaluated the costs and risks subjectively and therefore a sensitivity study was advised to identify the significance of each variable on the decisions. Any variables found to be significant in the selection of alternatives should then be confirmed by the operator, to ensure that the decisions are not made on the

wrong assumptions. However, because the decision was considered preliminary the client would not commit to any additional work. It was then suggested to the client that as soon as they had better information in terms of either costs or probabilities, these should be included in the analysis. A refinement of this method would therefore include more detailed evaluations of probabilities and consequences of failure in each process. This would make it possible to determine any effect on the final decision.

Such a refined evaluation would also include a verification of the fitness for purpose of each structure following the change in location and possible change in environmental conditions. This would include an assessment of the environmental conditions at the new location and a comparison with the old location. An assessment of fatigue life of risers and compatibility of remnant life with the new location would also be carried out. Piping stress analysis of the manifold pipe work subject to the new pressures and temperatures would be necessary as would pile capacity calculations to assess the suitability of the structural foundation for the new location.

6.7 Conclusions

The decision problem addressed in this case study was very early in the design life of and therefore required a preliminary evaluation of the alternatives to allow a high level decision to be made in conceptual terms. At such an early stage, the problem involved a significant number of uncertainties that were difficult to quantify. This would usually make any type of risk assessment very difficult. However, at such an early stage it is very important to carry out a good risk assessment, as it is easier to manage the risks now rather than later once preliminary design decisions have been made. In addition, the cost of managing the risks at conceptual design stage can be much lower.

Stakeholders were not considered an essential issue at this stage, as this was just a preliminary feasibility assessment of whether an important option should be considered further or not. However, due to the risks in terms of costs and environmental impacts that were at stake in the ultimate design, stakeholders were expected to play an important role in the final decision that was made. Therefore, it was believed that by using risk-based decision methods to support the preliminary decision at this stage that the audit trail would be available to gain support and consensus from the other stakeholders later when this was needed.

In this case study, the number of alternatives did not play a significant role in the way the decision was made. This decision was primarily a choice between re-using existing subsea facilities or not. There were no intermediate alternatives to consider.

As a preliminary evaluation, the important decision criterion was identified as being the "expected cost" of each alternative. This provided a simple but auditable basis for the conceptual decision to be made. It allowed the risk assessment and expert judgements to be integral to the decision-making without requiring costly gathering of additional information. This was not considered beneficial to the decision at such an early stage.

The use of decision trees as part of the structural analysis provided a structured and detailed method for evaluating the consequences of important uncertain events for each

of the alternatives. The process of defining the decision trees supported a rational evaluation of all the alternatives and possible risks involved in reusing the subsea infrastructure. In some cases, the process became almost iterative as one question further down a branch of the decision tree introduced ideas of alternatives higher up on a different branch. This aided the understanding of the decision problem and the implication of uncertain events on the overall consequences of the decision. In this case study there was a limited number of alternatives requiring a limited amount of data, therefore the decision trees were practical and very useful. However, even then in some cases they did become quite large and awkward to handle. If the problem had been any more complex, then it would have been impractical to use this method without robust computer assistance.

The main problem that had to be addressed in this case was the lack of concrete information. As mentioned previously, this lack of information made the risk-based decision even more important. The tools used to support the decision in this case were therefore selected to support the identification and gathering of information. Much of this information was expert judgement at this stage. However, the process then allowed the important information to be identified for further investigation at a later stage. This optimises the requirement and use of information in the decision process both at this early stage and later when more detailed information is available.

The important risks that were identified and assessed in this problem were the risks of damaging the facilities on removal so that they could not be re-installed. The subsequent risk of scheduling delays that would then result from having to order new equipment instead was also considered. Due to the lack of information and the preliminary nature of the assessment, it was not considered beneficial to carry out for example, a structural reliability assessment of the riser under removal loading. Neither was there sufficient documented information on the frequency of successful and unsuccessful removal operations. Therefore, experts with a number of years experience in carrying out these operations were asked to give their subjective opinions on the probability of success (and/or failure) for each operation. This was considered appropriate to the preliminary nature of the decision. The results of the risk assessment were directly incorporated into the decision criteria as "expected cost", which directly influenced the final decision.

By asking experts for their subjective opinions of likelihood and consequences inherently introduces preferences and perceptions. It is impossible to remove these from such experience-based data entirely and at such a preliminary level, it was not considered a serious problem. However, perceptions and preferences were controlled by having more than one expert and by using experts from different backgrounds. Then through the role of a third party facilitator I was able to control the preferences and perceptions of the experts by ensuring they came to agreement on the assessment of each risk. This meant that if there was not initially consensus then each expert had to justify their own point of view until all experts finally understood each other and could agree. This provided an effective method for controlling the subjectiveness of the assessment.

The decision-makers gained significant confidence in the recommended decision due to the structured manner in which the problem was addressed using the risk-based decision model. They therefore took the recommendations on board and used the decision trees to argue their case to their clients.

Sensitivity analysis was not carried out at this stage, although it was suggested to the client that a sensitivity study could be carried out especially on the probabilities. The costs and risks have been evaluated subjectively by APA engineers and therefore should be checked for suitability by both the installation contractor and the operator. However, because the decision was considered preliminary the client would not commit to any additional work. It was then suggested to the client that as soon as they had better information, in terms of either cost or probabilities, these should be included in the analysis. A refinement of this method would therefore include more detailed evaluation of probabilities and consequences of failure in each process. This would make it possible to determine any effect on the final decision.

The use of the risk-based decision model meant that risk was clearly accounted for in the decision. It is very likely that in the absence of such a model normal practice would have been to evaluate the alternatives based on cost only. The risks involved are however significant and therefore have a significant impact on the final decision.

The application of the risk-based decision model to this case study has shown that not all stages are relevant for all decisions. However, for the stages that were not relevant, it was still useful to have to consider whether it was relevant or not. For example in the case of considering stakeholders, without the decision model, stakeholders might never have been considered at all. As it was, careful consideration was made as to whether they should be accounted for now or later.

The use of a structured decision process to support the decision helped the decision-makers identify the key issues to be addressed and allowed the important decision criteria and alternatives to be identified and agreed. Not only did this promote ownership of the ideas, but also sharing of knowledge and understanding introduced new possibilities and ideas that might never have been thought of. It also helped understand of others opinions and perceptions and helped build consensus in the final decision.

The use of the risk-based decision model brought the significance of the risks to the fore and meant that the assessment of risks was an integral part of the decision process. The consideration of all of these issues meant that a clear audit trail could be produced of the way the decision was made. This could then be to be re-visited, understood and if necessary re-addressed at a later stage.

7 CASE STUDY 2

DEVELOPING A MAINTENANCE STRATEGY FOR VIADUCT CROSSBEAMS

7.1 Problem Definition

7.1.1 Identify problem or opportunity

The problem addressed by this case study was identified around ten years ago, during routine inspection of a group of viaduct crossbeams, which revealed significant deterioration of the waterproofing of the expansion joints. Water, contaminated with de-icing salts, had seeped into the concrete and ingressed through the concrete to attack the steel reinforcement. It takes many years for the corrosion process to pass through the stages of chloride ingress, depassivation of the concrete, corrosion of the reinforcement bars and finally delamination of the concrete from the reinforcement. It is only in the last two stages that the capacity of the crossbeam is significantly reduced.

Even at the time, the potential significance of the problem was understood and the engineers responsible for the management of the viaducts set out a plan for repair and maintenance of the crossbeams before their capacity was seriously compromised. However, each year, the requested funds were never fully supplied and the repair work fell behind schedule, allowing further deterioration. Finally, the backlog was so significant and the viaduct integrity, uncertain that we were asked to assess the current and future crossbeam integrity and to prioritise them for repair and strengthening.

7.1.2 Identify stakeholders in the decision

Due to the significance of the stretch of motorway of which these viaducts are a part, in terms of the UK's motorway network, a wide range of stakeholders had to be taken into account in the decision-making process. The decision, after all, had to be seen to minimise the consequences of any interim measures, repair work, and any failure should it occur. These consequences were in terms of finance, national and local politics impacts on commuters, haulage firms, local residents and the environment.

One of the first stages in preparing for the analysis, therefore, was to determine who was in the decision-making group and to what extent each person could and wanted to, influence the decision.

The external stakeholders included users of the viaducts (private, commercial and industrial), environmental pressure groups (campaigning for improved facilities for environmental and reduced congestion) and government officials (Local Councillors, MPs from local constituencies, etc.).

There are two main groups of internal stakeholders, the asset managers and the asset management group. The asset manager is the maintenance agent contracted by the Highways Agency to manage the route network to which these viaducts belong. The maintenance agent is responsible for the safety and maintenance of all the structures in the network including planning and allocating budgets to inspection, maintenance,

repair, strengthening and upgrading of all the network's structures. The asset management group is the committee responsible for allocating annual budgets for each asset manager including the highways agency network management division representatives, the network maintenance agent and council representatives.

7.1.3 Identify viable alternatives

The alternatives in this decision were the many viaduct crossbeams that required strengthening. However, in each financial year, more than one crossbeam could be strengthened to ensure best use of the annual budget. Part of the decision-making involved identifying whether several crossbeams on one viaduct should be strengthened at one time, thus limiting the disruption to traffic, or whether the absolute worst crossbeams should be strengthened at the same time, thus minimising the probability and consequences of failure. The combinations of alternatives were therefore far more numerous than the number of crossbeams requiring repair.

7.1.4 Formulate decision objectives and criteria

The decision criteria were identified very early on in the analysis through discussions with experienced bridge engineers and members of the asset management group who were trying to represent the views of external stakeholders (such as local business and industry) in addition to their own. In addition, previous work for the Scottish Office [108] was reviewed. The main criteria, on which the crossbeam maintenance scheduling decisions were to be based, defined in more detail below, were found to be:

- The cost of carrying out strengthening work
- The risk of crossbeam and hence viaduct failure if strengthening work is not done
- The cost of interim measures such weight restrictions, or propping if strengthening work is not carried out immediately.

7.1.4.1 Cost of Strengthening Works

Since one of the main issues in scheduling the viaduct crossbeams for strengthening is the optimal allocation of resources from the annual budget, the cost of carrying out the strengthening work on each crossbeam should be taken into account.

The factors that were identified to evaluate the cost of strengthening works included:

- the cost of actually carrying out the work (labour, material, equipment), as stated in the works budget,
- the cost of traffic management schemes during the works (lighting, signing, cones, etc.), provided by the assessing engineer's estimates,
- the cost of traffic delays during the works (imaginary cost), taken from look-up tables for costs of diversion and cost of delays. These were based on the assessing engineer's estimate of the likely traffic flows, the make up of those flows, diversion lengths, road types, etc.

All of these factors can be aggregated directly to represent the overall cost of strengthening for the particular strengthening project under consideration.

7.1.4.2 Cost of Interim Measures

It was decided to consider only viaduct crossbeams that have failed the standard capacity assessment. Therefore, until the strengthening work was completed, it may have been necessary to implement certain interim measures. These could include weight restrictions, lane restrictions, propping, etc. The costs of implementing such interim measures would be saved if strengthening work was carried out.

The costs associated with implementing any necessary interim measures were identified. These included costs associated with traffic disruption (real and imaginary costs due to delays and diversions) incurred by the implementation of weight or lane restrictions on and around the bridge. In addition, the costs of implementing and maintaining road signs and markings to indicate weight or lane restrictions or the cost of propping were also considered. These costs would have been saved if the bridge was strengthened.

The costs associated with the traffic disruption caused by the implementation of interim measures were calculated from Quadro, a specialised software program based on the assessing engineer's estimate of the likely traffic flows, the make up of those flows, diversion lengths, road types, etc. The cost of implementing and maintaining the interim measures was taken directly from estimates made by the assessing engineer.

All of these factors can be aggregated directly to represent the overall cost of interim measures for the particular strengthening project under consideration.

7.1.4.3 Risk of Crossbeam Failure

Despite a viaduct crossbeam failing an assessment, it is not feasible in all cases to implement interim measures, such as weight restrictions, to maintain safety. In these cases, the probability and consequences of failure can be high. In other situations, the probability of the crossbeam failing under standard operation is considered acceptable. The scheduling process will carefully calculate the probability of each crossbeam failing under standard operation and assess the consequences of failure. This then provides a comparison with the cost of interim measures, as a bridge without interim measures will have both a higher probability of failure and higher consequences of failure (e.g. more traffic would continue to use the bridge subjecting more people to the risk). This therefore should be taken into account in establishing optimum repair schedules. Obviously, this risk will be greatly reduced if the strengthening works are carried out.

Early on in the assessment, a separate study was carried out to identify all the consequences of failure and the factors influencing their magnitude. The results of this study indicated that due to all the viaduct crossbeams being part of the same road network and therefore being subjected to very similar levels of traffic loading, the consequences of failure of different crossbeams were very similar. There would of course be some differences depending, for example, on whether the viaduct crossed over another road (and the size of that road), a railway line or a river/canal. These

differences were considered negligible and therefore it was recommended that the focus of the risk assessment be on the probability of failure instead. A detailed description of the method adopted for the calculation of failure probability is presented in Section 7.3.

The main constraint on the decision was the budgets given for that year. However, the constraints on safety influenced other factors such as traffic disruption and impact on the local community.

7.2 Structural Analysis

Due to the number of alternatives available in this decision problem, it is not possible to illustrate it in its entirety. Therefore, Figure 12 shows a sample of the much more complex decision tree representing this decision problem.

7.3 Uncertainty and Probabilistic Analysis

The uncertainties typically involved in the design or assessment of bridges arise from:

- the inherent variability of loads and material resistance parameters;
- uncertainties in the deterioration of bridge components over time;
- uncertainties in analysis models used for determining the load effects and capacities;
- uncertainties in measurement and inspection techniques.

In view of these, it is possible that a bridge component could fail from an adverse combination of extreme values of the variables.

In a traditional codified design or assessment, such as in BD 44/95 [124], the safety of a bridge component is ensured through using partial safety factors to protect against extreme variations of the variables. Safety under a particular limit-state is checked using a design compliance equation of the form:

$$F_C \cdot function\left(\frac{f_k}{\gamma_k}\right) \geq \gamma_{f3}\left(effects\ of\left(\gamma_{fD} \cdot Q_D + \gamma_{fL} \cdot Q_L\right)\right) \qquad \textbf{Equation 5}$$

Where, f_k is the characteristic material strength

Q_D is the nominal dead load

Q_L is the nominal live load (traffic load).

γ_k is the material partial factor for each material type (e.g. concrete and reinforcement) and accounts for the uncertainty in material parameters.

γ_{fD} is the partial factor used to account for the uncertainty in dead load.

γ_{fL} is the partial factor used to account for the uncertainty in live load.

γ_{f3} is the partial factor used to account for uncertainty in the evaluation of load effects (analysis uncertainty).

F_c is the condition factor used to account for the reduction in the capacity of the component due to deterioration. Alternatively, the component capacity can be calculated using the net cross-section allowing for deterioration.

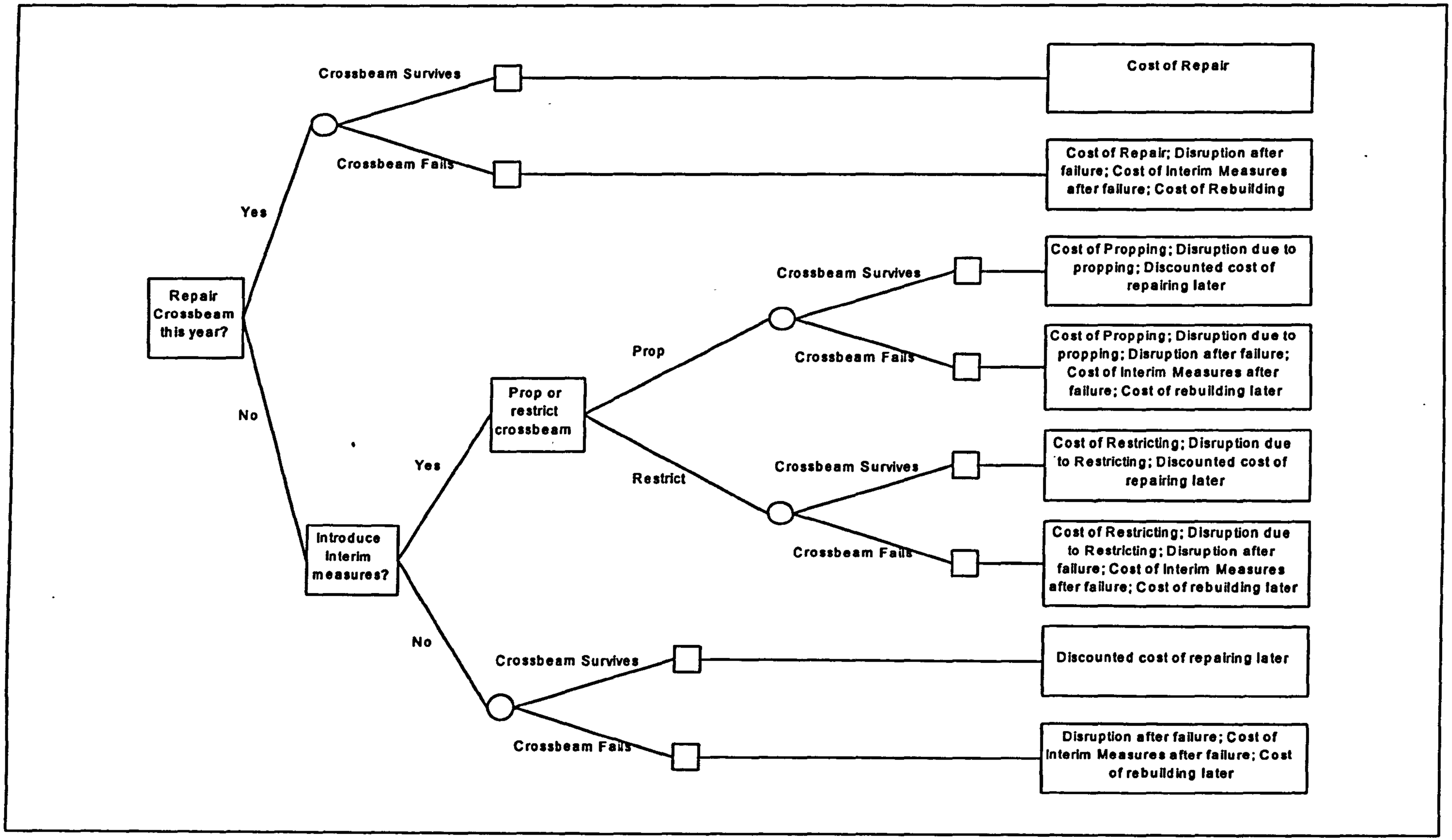


Figure 12: Decision Tree representing a sample of the decision problem

Structural reliability methods attempt to rationally treat the various sources of uncertainty involved in a design or assessment process. In a reliability analysis, the partial factors as in Equation 5 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.

The reliability analysis approach is closely linked to the limit-state concept. For each limit-state (or failure mode) of a bridge component (e.g. crossbeam), a separate reliability analysis is carried out to evaluate the probability that this limit-state will not be reached. These results can then 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

Error! Objects cannot be created from editing field codes. **Equation 6**

and the probability of failure is calculated as

$$p_f = Probability[Z \leq 0] \qquad \textbf{Equation 7}$$

Where, Z is the "safety margin".

p_f is the probability of failure.

The component's resistance is evaluated as a function three uncertain parameters sets:

- material parameters f_k (e.g. strength of concrete, yield strength of reinforcement/tendons, etc.)
- geometrical parameters g (e.g. effective depth, cover, area of steel, etc.)
- deterioration parameters d (e.g. corrosion rate, delamination growth rate, etc.)

These are considered as random basic variables and are described using appropriate probability distributions. On the loading side the uncertain parameters are grouped together as the dead load Q_D, the super-imposed dead load Q_{SD} and the traffic load Q_L.

These are also treated as random variables. In addition, the variables B_R and B_Q have been introduced to model, to represent the uncertainty in the capacity calculations and in the analysis method used for calculating the load effects, respectively. A number of efficient techniques are now available for calculating the probability of failure as expressed in the above equation.

The main components involved in reliability analysis of a viaduct crossbeam are:

- Modelling of dead and live loading on the viaduct
- Modelling of the strength of the crossbeam under different failure modes
- Modelling of deterioration of the crossbeam
- Identifying and quantifying uncertainties in the variables

- Calculating failure probabilities (or reliability) with respect to each failure mode and the overall probability of failure.

The approaches used during this case study are discussed in the following.

7.3.1 Modelling of dead and live loading on the viaduct

7.3.1.1 Traffic load modelling

For loaded lengths of more than 25m (which was typical of the viaducts under consideration), the maximum lane loading occurs due to a combination of two or more vehicles. The traffic load effect for the section considered depends on the total traffic flow rate, composition of different vehicle classes, the weight and length of individual vehicles. Since these quantities are random, the traffic load effect is also random.

In a reliability analysis, the probability distribution of the annual maximum traffic load effect is required. Initially, the annual maximum traffic load effect distribution was assumed to follow a Gumbel distribution based on code specified load. This model was adequate to provide correct sensitivities but not necessarily accurate reliability values. Therefore, a future improvement to the analysis method was planned to develop the probability distribution of the annual maximum traffic load effect by using a Monte-Carlo simulation technique based on the traffic data specific to these viaducts.

7.3.2 Modelling Of The Strength Of The Crossbeam Under Different Failure Modes

The ultimate limit-states of interest for the RC crossbeams are: (1) Flexure, (2) Shear and (3) Bond. The models for flexure and shear are essentially those given in BD 44, but with the partial factors removed. The model for bond was developed based on beam tests carried out at Westminster University [125].

7.3.2.1 Flexure

The neutral axis position of a Reinforced Concrete section under flexure was calculated using the method of section analysis based on the assumptions given in BD 44:

- The strain distributions in the concrete in compression and in the steel reinforcement are derived from the assumption that plane sections remain plane.
- The stresses in concrete are calculated from the strains using the stress-strain curve for concrete given in figure 1 of BD 44 with the partial factor γ_{mc} set to unity.
- The tensile strength of concrete is ignored.
- The stresses in the reinforcement are calculated from the strains using figure 2 of BD 44 for reinforcement with the partial factor γ_{ms} set to unity.
- The moment of resistance of an under-reinforced section is then calculated as in BD 44, Section 5.3.2.3 (ignoring the contribution of compression reinforcement)

$$M_u = f_y A_s z \qquad \textbf{Equation 8}$$

Where, A_s is the area of tension reinforcement (mm^2)

f_y is the yield strength of reinforcement (N/mm^2)

z the lever arm (mm)

7.3.2.2 Shear

The shear capacity of a Reinforced Concrete section is calculated based on the empirical formulae given in BD 44, Section 5.3.3.2 with the partial factors set to unity, as below.

The shear strength of a section with effectively anchored longitudinal reinforcement in excess of that required to resist the coexistent bending moment at the section is:

$$V_u = \xi_s v_c bd + f_{yv} A_{sv} \frac{d}{s_v}$$

$$v_c = 0.24\left(\frac{100A_s}{bd}\right)^{1/3} (f_{cu})^{1/3} \qquad \textbf{Equation 9}$$

$\xi_s = (500/d)^{1/4}$ but not less than 0.7

Where, b is the width of the beam (mm)

d is the effective depth (mm)

f_{cu} is the cube strength of concrete (N/mm^2)

A_{sv} is the area of shear reinforcement (mm^2)

A_s is the area of main reinforcement (mm^2)

f_{yv} is the yield strength of shear reinforcement (N/mm^2)

s_v is the spacing of stirrups (mm)

The limits on the maximum shear stress v_c and the checks for effectiveness of shear reinforcement are made in accordance with BD 44.

7.3.2.3 Bond

A bond exists between reinforcement and concrete creating the bar end anchorage and composite interaction between steel and concrete along the bar. The corrosion of the reinforcement causes a reduction in the bar section, reducing the tensile strength. The by-products of the corrosion process expand, cracking the concrete cover. These two factors combine to reduce the bond strength of the reinforcement affecting the composite interaction and anchorage strength on which the design loads were based.

Reference [138] describes experiments carried out to correlate the bond strength with the loss in reinforcement section for geometries with and without stirrups. In the experiments, the main bars were corroded but the stirrups were not. The equations that fitted to the experimental results by linear regression relate the attack penetration, x (decrease of bar radius) to the bond strength, f_b. If the stirrups are also corroded then the bond strength will fall between the above two cases. Expressions were, therefore, derived by linear regression [138] to evaluate the bond strength for any condition of

main reinforcement and any condition of stirrups. A further relationship was developed between the standard bond strength along the length of the beam and the increased bond strength at the support zones caused by the external pressure at the support reactions.

These theories were supplemented by beam tests carried out at the Westminster University, the results of which are given in [125]. This also describes the methodology adopted for calculating the bond capacity of a Reinforced Concrete section.

The anchorage length L_a required to sustain full tensile capacity for an undelaminated reinforcement is first evaluated using:

$$L_a = \frac{A_s f_y}{O B} \qquad \textbf{Equation 10}$$

where, A_s is the area of each bar of main steel reinforcement (mm^2)

f_y is the yield strength of steel reinforcement (N/mm^2)

O is the perimeter of each bar of main steel reinforcement (mm)

B is the undelaminated bond strength of concrete, calculated as

$$B = \beta\sqrt{f_{cu}} \qquad \textbf{Equation 11}$$

where, β is the Bond coefficient (taken as 0.7 here),

When part of the reinforcement in the anchorage zone is delaminated, an additional required anchorage length is determined. A "usage factor", μ, is then calculated to determine the ratio of the total anchorage length available and the anchorage length required:

$$\mu = \frac{(\eta L_d) + L_u}{L_a} \qquad \textbf{Equation 12}$$

where, L_d is the delaminated length of reinforcement (mm)

L_u is the undelaminated length of reinforcement (mm)

η is the factor on bond strength = 0.32 for delaminated bars.

Finally, the bond capacity of the reinforcement is calculated by:

$$B_c = \mu\ A_s f_y \qquad \textbf{Equation 13}$$

The value of 0.32 for η is based on a limited number of beam tests carried out by Westminster University for the Highways Agency. The effects of the loss of shear links and clamping on the bond strength were not accounted for at this stage.

The failure of a crossbeam under bond is checked by comparing the bond capacity from equation 10 with the force in the bars due to the applied loading evaluated as

$$F_x = \frac{M}{Z} + \frac{V Cot\vartheta}{2} \qquad \textbf{Equation 14}$$

where, $Cot\vartheta = \frac{V}{A_{sv} f_{yv}} \frac{S}{Z}$ $\quad 1 < Cot\vartheta \leq 3$ **Equation 15**

M is the moment in the beam (N-mm)

Z is the lever arm of beam section (mm)

V is the shear force in the beam (N)

A_{sv} is the cross sectional area of the legs of a shear link (mm^2)

F_{yv} is the yield strength of shear reinforcement (N/mm^2)

S is the spacing of shear links

7.3.3 Modelling of Deterioration of the Crossbeam

The alarming rate of bridge component deterioration has inspired considerable research into the causes, prevention, and prediction of deterioration. All these affect the value and certainty of the calculated structural reliability.

Steel embedded in concrete is normally passivated (coated with oxide) by the strongly alkaline pore water. Deterioration of reinforced concrete bridges is often caused by the corrosion of steel reinforcement where the passivation has been breached. The two main causes of de-passivation involve chloride ingress and carbonation of the concrete. Since the deterioration of bridge components is such a key factor in the evaluation of risk and reliability, much attention has been focused on this area.

7.3.3.1 Carbonation

Carbonation is the entry of carbon dioxide into concrete, which reduces the structure's alkalinity. When the carbonation front reaches the steel reinforcement, the passivation effects of the concrete are lost and reinforcement corrosion can start if moisture and oxygen are present. Martin, Rausen and Schiessl [126], Klopfer [127] and Parrott [128] predicted the rate of penetration of CO_2 based on Fick's law as:

$$x = (2Dt)^{0.5}$$ **Equation 16**

Where, x = depth of penetration (mm)

D = diffusion coefficient (mm^2/year)

t = time (years)

According to Mallett [129], diffusion coefficients are notoriously inconsistent. They can only be calculated with confidence where historical data on carbonation depths are available [130], but it can be a problem to find such consistent data.

Cady and Weyers [131] presented another model based on experimental results by Somerville [132] that accounts for the water - cement ratio and the depth of cover.

Rostam and Geiker [133] gave a model for carbonation rate that also accounted for concrete porosity. Skaarup and de Fontenay [134] accounted for differences in water cement ratios, curing times and types of exposure. Other equations were also developed

[128] to consider exposure, surface finish, water/cement ratios, curing, fly ash content and climate.

Parrott [128] also calculated the expected depths of carbonation based on the concrete compressive strength, the effects of atmospheric CO_2 levels in relation to the concrete's CO_2 binding capacity, and the effect of temperature.

7.3.3.2 Chloride Ingress

The common source of chloride, if not from the sea, is from de-icing salt, either leaking through faulty waterproofing or deck joints, or splashed up by traffic. This was such a major problem on the viaducts under consideration that eventually, de-icing salts were banned from the viaducts. The presence of chloride ions causes depassivation of steel even if the pore solution is highly alkaline.

Pocock and Gibbs [135] plotted chloride distribution curves from samples taken at distances from the concrete surface and found that Fick's second law of diffusion applies, as shown in Equation 15:

$$\frac{dC}{dt} = \frac{D_c d^2 C}{dx^2}$$ **Equation 17**

Where, C = chloride ion concentration (% cement weight), at a depth, x after time, t

D_c = chloride diffusion coefficient

Thoft-Christensen et. al. [136], Cady and Weyers [131], Rostam and Geiker [133] and Miyagawa [137] took this further and presented the solution of the above differential equation. However, Rostam and Geiker [133] made an adjustment to allow for the surface chloride concentration varying over time.

Thoft-Christensen et. al. [136] then went on to suggest that the corrosion initiation period was based on the equilibrium chloride concentration on the concrete surface, the initial chloride concentration, the critical chloride concentration and the concrete cover.

Following the start of corrosion, Thoft-Christensen et. al. [136] and Rodriguez et. al. [138] modelled the diameter of the reinforcement bars, DI(t) at time t by applying Faraday's Law in terms of initial diameter, corrosion coefficient and the corrosion rate.

Fick's second law of diffusion is widely accepted as the best method of modelling the diffusion of chloride through concrete. However, Wood [139] stated that it is a crude simplification of the processes that led to chloride ingress in real structures. Concrete is not a stable, inert material and diffusion is only one of five processes that lead to chloride ingress [140, 133]. Other processes include capillary suction, permeation, evaporation and backwards diffusion. Fick's Law's appropriateness was also questioned in [141] on the grounds of chemistry.

The models described above relate to an average deterioration of reinforcement in concrete. An important aspect though, is the additional pitting of reinforcement. This could have more influence on structural integrity, due to increased weakening of the reinforcement locally. This can be accounted for by defining a ratio, R, of the

maximum penetration (due to pitting), PC_{max} and the average penetration, PC_{av}. This has been estimated at between 4 and 10 [142].

Due to the questions raised in the above review, as part of this project additional corrosion samples were taken from crossbeams that have already been removed to be replaced. Based on all this information, deterioration models were developed [143] to allow the most appropriate prediction of corrosion and delamination growth. The time of initiation of corrosion was calculated based on the chloride measurements and cover data. The rate of corrosion (mm^2/year) was assumed constant and is determined for the longitudinal and shear reinforcements as:

$$r_{main} = -C_{main}(E + 260)^2 \qquad r_{shear} = -C_{shear}(E + 260)^2 \qquad \textbf{Equation 18}$$

where: C is the Corrosion Coefficient (mm^2/year)

E is the half-cell potential in mV.

The final area of reinforcement, accounting for corrosion loss over a period of t years after initiation, was then based on the as-built cross-sectional area of reinforcement and the corrosion rate for the main or shear steel over time, as shown in equation 19 below:

$$A_{s,t} = A_{s,o} + r_{main} \cdot t \qquad A_{sv,t} = A_{sv,o} + r_{shear} \cdot t \qquad \textbf{Equation 19}$$

where: $A_{s,o}$ is the as built cross sectional area of tensile reinforcement

$A_{s,t}$ is the remaining cross sectional area of tensile reinforcement at time t

$A_{sv,o}$ is the as built cross sectional area of shear reinforcement

$A_{sv,t}$ is the remaining cross sectional area of shear reinforcement at time t

The delamination at any point in time is calculated from a measured initial delamination (from the last delamination survey) and then growing the delamination over time using an appropriate delamination growth rate. For this analysis, for simplicity, only delamination growth in the direction of the main reinforcement was considered. All of the reinforcement bars were assumed to be equally delaminated across the width of the crossbeam.

It should be noted that this delamination model was not coupled with the corrosion model while in reality corrosion leads to delamination. Furthermore, the delamination is assumed to "grow" over time along its entire boundary, which is not corroborated by the field data. These limitations would have to be addressed in a final analysis.

7.3.4 Identification And Quantification Of Uncertainties In The Variables

An important task in reliability analysis is to identify the significant sources of uncertainty, which influence the probability of failure, and model these through random variables each of which is described using a probability distribution. A number of important random variables were identified for use in this reliability analysis. The probability distributions for these variables were obtained by collecting and

synthesising published information. The provisional probability distributions are summarised in Table 22. The basis of these models is discussed in the following.

Traffic Loading - The probability distribution of the traffic load effect due to the static weight of vehicles is assumed to follow a Gumbel distribution. The static load effect is multiplied by an Impact Factor, to account for the dynamic effects.

Impact Factor - The total load effect experienced by the bridge could be considerably increased by the bridge dynamic response during a vehicle crossing. To account for this, the load effect calculated using the static vehicle weight is multiplied by an "impact factor" (defined as the ratio of the total dynamic load effect to the static load effect). The impact factor here is applied to the gross weight of a vehicle, in contrast to the impact factor of 1.8 applied on the heaviest axle weight used in deriving the HA loading given in BD37. The impact factor is a function of the vehicle suspension and speed, bridge dynamic characteristics and the surfacing condition. Since the vehicle characteristics are unknown, the impact factor was modelled as a function of the bridge span and surfacing condition with probability distributions obtained from [144].

Dead Load - The total dead load is made up of: (i) the deck element weight, (ii) the deck beam weight, (iii) the surfacing weight and (iv) the weight of other non-structural elements. The probability distributions for these were obtained from [145, 146].

7.3.4.1 Material and Geometric Parameters

Material parameters such as strength of concrete, yield strength of steel/ reinforcement/ tendons have been modelled as random variables. Published data is available on the probability distributions of these variables. The values given in Table 22 are considered appropriate for bridges with no significant deterioration and for which the material grade is known. The data on geometric parameters has been obtained from judgement and limited published data, for example [146].

7.3.4.2 Deterioration Parameters

The probability distributions assumed for the deterioration parameters are shown in Table 22. A high coefficient of variation has been used for the corrosion coefficient to account for the uncertainty in the model to calculate the initiation time, the corrosion rate and the actual measurements on which the calculations are based. The probability distribution for the corrosion coefficient was taken from a statistical analysis of the deterioration data obtained from previous repair carried out on these crossbeams [143]. The probability distribution for the delamination rate was taken from a statistical analysis of data from four crossbeams on a different viaduct.

7.3.4.3 Model Uncertainty

The uncertainty in the analysis method used for calculating the load effect was accounted for by B_Q. The distribution for this parameter was chosen from judgement and from comparison with published studies [145] and assumes that load effects are calculated using a good elastic "grillage" model of the bridge.

The uncertainty in the capacity equations given by the code has been taken into account through B_{rb} for bending and B_{rs} for shear. The model uncertainty in bond capacity is expressed through the β factor (bond coefficient) and the η factor for the delaminated bars. The distributions proposed for these are based on judgement.

It is important to collect more information on the capacity uncertainty, particularly for shear and bond failure modes for which the capacity equations have been obtained by empirical fit (often lower bound) to test results. The model uncertainty in shear and bond is generally higher than that for flexure and also the probability of failure in these limit states is seen to be very sensitive to model uncertainty parameters.

	Variable	Distribution	Mean	COV
Live Loads	Annual maximum live load effect	Gumbel	0.85×HB25	0.04
	Impact Factor	Normal	1.10	0.10
Dead Loads	Effect of deck load	Lognormal	Nominal	0.06
	Effect of beam load	Lognormal	Nominal	0.04
	Effect of surfacing load	Lognormal	1.1x nominal	0.20
	Effect of finishing load	Lognormal	1.1x nominal	0.10
	Density of crossbeam	Lognormal	Nominal	0.05
Material Properties	Strength of concrete f_{cu}	Lognormal	Nominal+10Mpa	0.15
	Strength of reinforcement f_y/f_{yv}	Lognormal	1.1x nominal	0.06
Geometrical Properties	Diameter of main reinforcement	Normal	Nominal	0.015
	Area of shear reinforcement A_{sv}	Normal	Nominal	0.03
	Depth to main reinforcement d_{eff}	Normal	Nominal	σ = 10 mm
	Depth of crossbeam section	Normal	Nominal	σ = 15 mm
	Spacing of shear reinforcement	Normal	Nominal	σ = 15 mm
Model Uncertainties	Load effect B_Q	Lognormal	1.0	0.05
	Bending calculation B_{rb}	Lognormal	1.0	0.05
	Shear calculation B_{rs}	Lognormal	1.0	0.10
	Bond coefficient, β	Lognormal	0.7	0.10
	Factor on delaminated bond strength, η	Lognormal	0.32	0.15
Deterioration Model	Corrosion coefficient of main steel, C_{main}	Lognormal	$7.0*10^{-5}$ $mm^2/yr/bar$	0.91
	Corrosion coefficient of shear links, C_{shear}	Lognormal	$7.0*10^{-4}$ mm^2/yr	0.75
	Rate of delamination growth	Normal	30 mm/yr.	1.50
	Uncertainty in measured delamination	Normal	0.0	σ=50 mm

Table 22: Probability distributions of basic variables

7.3.5 Reliability Analysis

The probability of failure as expressed in Equation 3 was calculated in this case using FORM/SORM methods. These are a group of 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.

The computational procedure of FORM/SORM methods is summarised in Appendix 3, see also [147]. The analysis gives the probability of failure p_f and the "reliability index" β which is related to p_f through,

$$p_f = \Phi(-\beta) \qquad \textbf{Equation 20}$$

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 X_i 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, which would cause the failure of a component.

In the analysis, computer routines were developed for calculating the load effects (bending moment and shear force) and crossbeam capacity under bending, shear and bond. These were linked with the general purpose reliability software STRUREL [148] to produce a tool for reliability analysis of the viaduct crossbeams.

The results of reliability indices are presented and discussed in the next section. The results of the sensitivity factors are presented in section 7.6

7.3.6 Results

Reliability analysis was carried out for one specific geometrical type of reinforced concrete viaduct crossbeam for the limit-states of flexure, shear and bond. For each limit state, the most critical cross-section position along the crossbeam was selected.

For the flexure limit state, the cross-section selected was close to the column of the middle span that was in hogging. For the shear limit state, a cross-section of the crossbeam in the middle span was chosen for the analysis. For the bond limit state, the cross-section selected was towards the centre of the middle span from the column supporting the middle span.

For flexure, shear and bond limit-states, the analysis was performed for three conditions of the crossbeam: (i) as-built condition (ii) present condition with some loss of strength due to corrosion of reinforcement and delamination, and (iii) future condition with further corrosion of reinforcement and delamination in the future years. For the bond limit state, analyses were carried out for differing degrees of initial delamination in the present condition. In addition, a case was analysed assuming that the crossbeam was fully delaminated in its present condition.

The results from these analyses are presented below in the form of the change in reliability index over time. Since the input distributions were not accurate at this stage for all the variables (especially loading and deterioration), the reliability index was normalised by the as built reliability index instead of using the absolute results.

7.3.6.1 Flexure Limit State

The reliability of the crossbeam was calculated at different points in time in the future. The corrosion of longitudinal reinforcement over time was calculated using the deterioration model given in Section 7.3.3, assuming that corrosion initiated in 1986. The loss of concrete section in the compressive zone had only a marginal influence on bending capacity.

Parametric reliability analyses were carried out to study the variation in reliability due to deterioration over time. The results for "low", "medium" and "high" rates of corrosion were assessed and are shown in Figure 13 (i.e. from -290mV (low) to -390mV (high)). These results revealed that the reliability decreased significantly with time in the first 5 to 10 years after the initiation of corrosion. The decrease in reliability was more pronounced only for the "medium" and "high" corrosion rate cases and showed almost no reduction when the corrosion rate was "low". These results, however, do not imply that the reliability will not decrease if the half-cell value is more positive than -250. This depends to some extent on the initial capacity ratio of the crossbeam and the proportion of live load carried by the crossbeam.

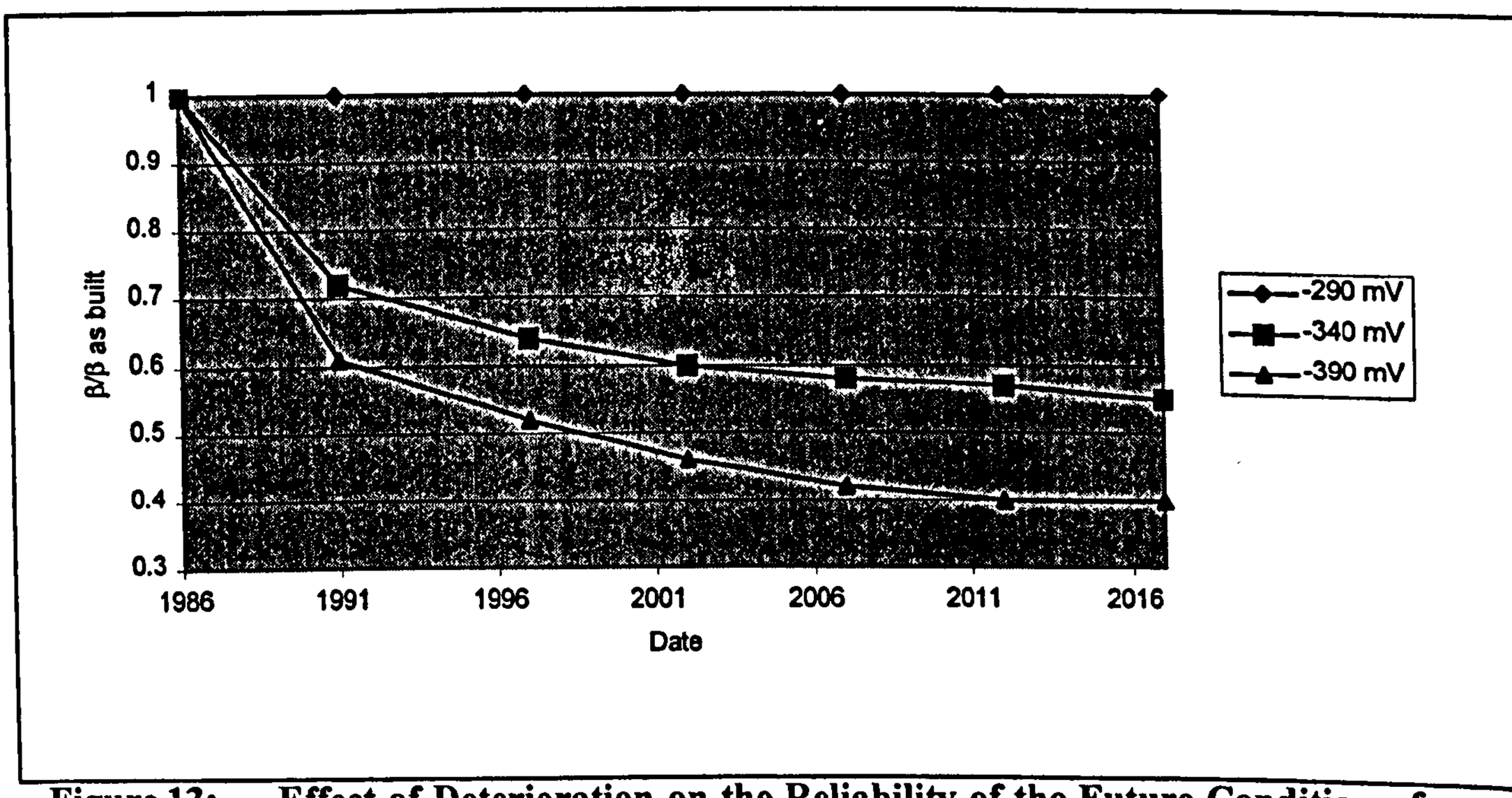


Figure 13: Effect of Deterioration on the Reliability of the Future Condition of the Crossbeam: FLEXURE LIMIT STATE

7.3.6.2 Shear Limit State

The reliability of the crossbeam at different points in time in the future was calculated for the shear limit-state. The corrosion of reinforcement over time was calculated using

the deterioration model given in Section 7.3.3, assuming that corrosion initiated in 1986. The loss of concrete section in the compressive zone was not included.

Parametric studies were carried out to study the variation in reliability due to deterioration over time. The effect of different corrosion rates on the reliability of a crossbeam, analyses were assessed for half-cell values ranging from -290mV (low) to -390mV (high). The results for "low", "medium" and "high" rates of corrosion, presented in Figure 14, showed that the decrease in reliability with time was of the same order for the shear case as the flexure case. The decrease in reliability was more pronounced for the cases of "medium" and "high" rate of corrosion.

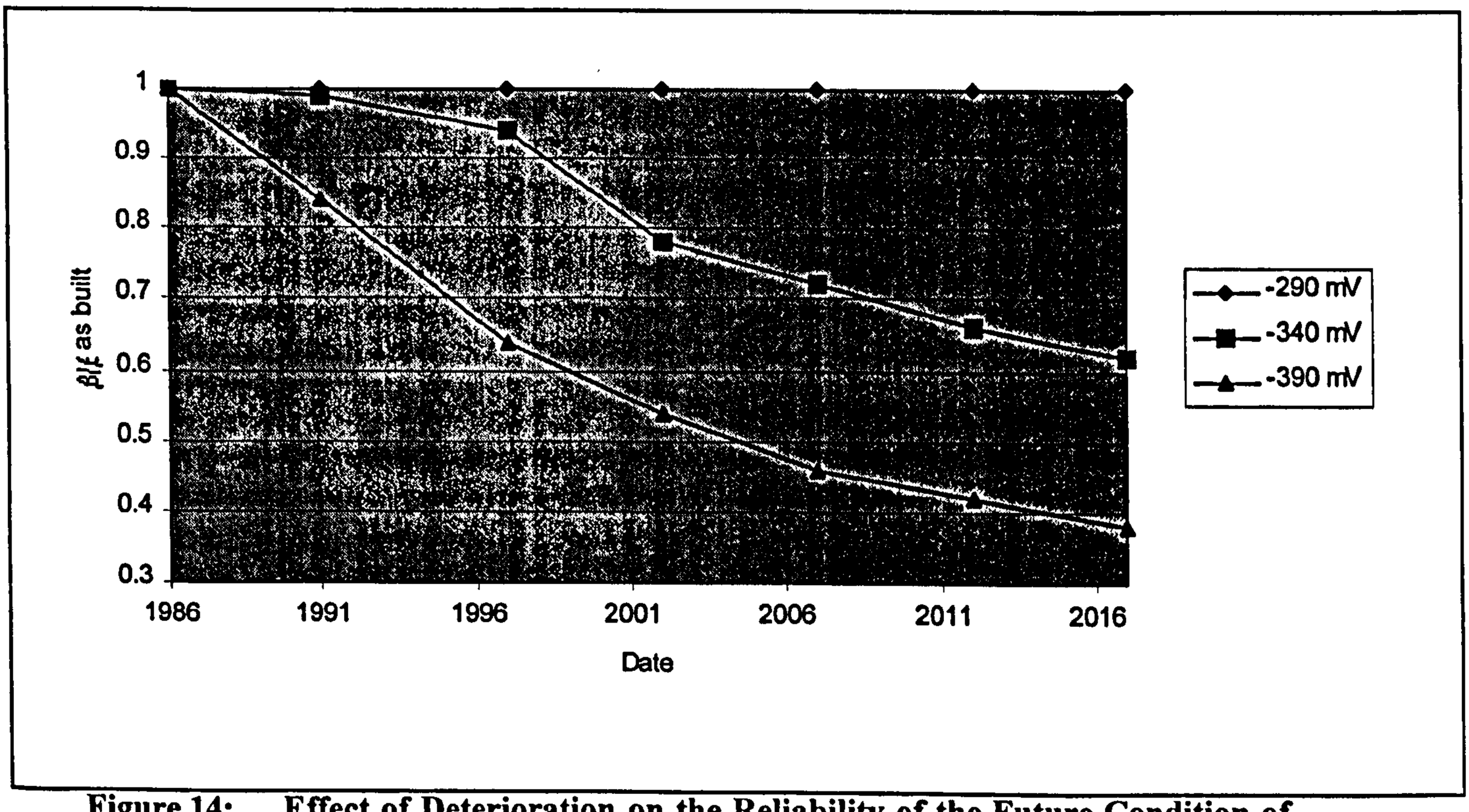


Figure 14: Effect of Deterioration on the Reliability of the Future Condition of the Crossbeam: SHEAR LIMIT STATE

7.3.6.3 Bond Limit State

The reliability of the crossbeam at different points in time in the future was studied for the bond limit-state using the deterioration model given in Section 7.3.3, assuming that corrosion initiated in 1986. The loss of concrete section in the compressive zone was not included.

Parametric reliability analyses were carried out to study the variation in reliability due to deterioration over time. The results for "low", "medium" and "high" rates of corrosion, presented in Figure 15, showed that, for "medium" and "high" corrosion rates, the reliability dropped quite dramatically with time. For the "low" corrosion rate, however, the reliability stayed initially unaffected, then dropped quite suddenly once a critical level of delamination was reached with the crossbeam failing in bond. As the delamination exceeded the critical area, the reliability level stabilised.

Examination of the design point values of the variables showed that, if the anchorage zone was moderately delaminated, it was likely to result in a combination of bond and bending failure. The bars with the shortest minimum anchorage length (with respect to the considered section) were likely to fail by bond (slipping) but the bars with the longer minimum anchorage length were able to mobilise enough bond strength to resist slipping. The final failure of the section occurred by the yielding of the longer bars.

The effect of high initial delamination was studied by considering the anchorage zone to be fully delaminated in its present condition. It was therefore evident that, when the initial area of delamination was small, reinforcement bars mobilised their full tensile capacity and the failure was likely to be of flexure type. When the area of delamination increased gradually, there was a stage when the failure mode changed over to a bond type. The point at which this change over happened depended on the section being considered, the length of the bars and the force in the bars. The loss of shear links (not considered here) could have initiated an early change over to the bond failure mode, while the clamping of bars would have delayed it. However, when the corrosion rate was high, the failure was more likely to be one of flexure type with the reliability dominated by the uncertainty in corrosion rate.

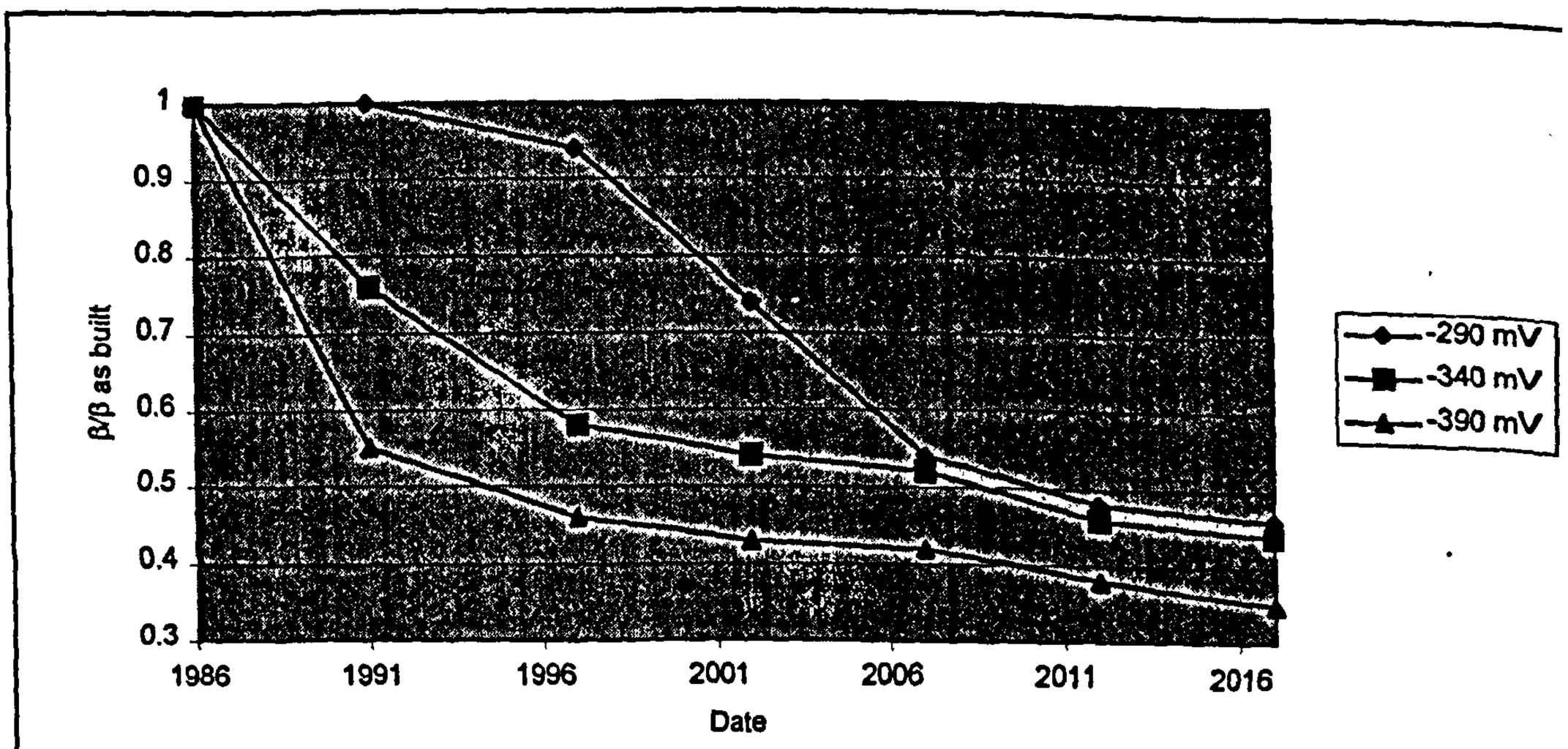


Figure 15: Effect of Deterioration on the Reliability of the Future Condition of the Crossbeam: BOND LIMIT STATE

7.4 Utility/Value Analysis

It became clear very early on that the governing decision factor, in the eyes of the identified decision-makers, was the probability of structural failure. The probability to be addressed related more to identifying a minimum acceptable, or target reliability, and scheduling repairs before the date at which the crossbeam was expected to reach that state. It did not involve significant trade-offs with the cost of repair and the cost of

interim measures. The cost of interim measures was obviously an important influence in the decision problem, there was in fact a very low tolerance to the implementation of interim measures, apart from propping. The route network under consideration was so significant that the prospect of imposing weight restrictions would have created such extreme traffic chaos that it was only considered acceptable as a last resort, in an emergency. The cost of repair and strengthening works was also considered only in terms of the effect it had on the remaining annual budget. Lower cost, lower risk projects may at times be brought forward to make the best use of the budget, if there was less benefit in bringing forward a more costly higher risk project. The values assigned to the decision criteria were, therefore quite clear.

7.5 Selection of the "Best" Alternative

Two problems remained before the best alternative could be selected:

1. To identify the minimum acceptable reliability at which point the crossbeam would have to be strengthened, propped or restricted irrespective of cost or impact.
2. To produce a rationale for deciding when it was beneficial to repair a crossbeam before its latest acceptable repair date and when it was better to leave it as long as possible until its latest acceptable repair date.

7.5.1 Definition of a target reliability level

In order to develop a reliability-based repair strategy, it is necessary to establish the latest intervention date by which the crossbeam must be repaired. For each crossbeam, a reliability profile can be produced by performing a number of reliability analyses corresponding to different points in time. The point in time when the computed reliability of a crossbeam falls below the target reliability level is taken as the intervention date. The minimum value from all limit states at the worst position in the crossbeam gives the latest intervention date for the crossbeam.

Bridge codes and standards in the UK do not currently specify target reliability levels, therefore it is necessary to determine an acceptable level. The problem in choosing a target reliability level is determining how safe is safe enough. Complex technical, social, economical and political issues need to be considered rationally. Three main approaches are usually adopted for determining a target reliability level:

- Socially acceptable risk levels derived from historical data.
- Calibration to existing codes.
- Economic optimisation combined with decision analysis.

7.5.1.1 Historical failure statistics

Historical failure data can be analysed to establish what level of risk has been accepted in the recent past. This then becomes a guide to what may be acceptable in the future. Where there is inadequate data, acceptance levels can be established by comparing risk levels implicit in different areas of activity such as driving by car, flying in an

aeroplane, working on an offshore platform, etc. This approach was used by Menzies [149] to establish target reliabilities for short span bridges in the UK.

There are a number of difficulties in using this approach:

1. Identifying who has accepted the risk in the past (industry, government or general public) is a problem. What is acceptable to the industry may not be acceptable to the regulator or the government. What one group of the population deems acceptable may not be acceptable to other groups. Additionally, what has been accepted in the past may not necessarily be acceptable in the future.

2. Defining what has been accepted is a problem. Historical failure data changes with time and shows abrupt changes in failure rates before and after a major accident.

3. Historical data represents generic conditions therefore it is difficult to relate failure rates to the specific environments and operating and maintenance regimes under which a structure or facility operates at present.

4. The methods of design and construction, and the operating and maintenance procedures have evolved over time. It is likely that the factors that contributed to a failure in the past are no longer relevant in the future.

5. There are also additional philosophical difficulties in relating historical failure rates to failure probabilities computed from a reliability analysis.

7.5.1.2 Calibration to existing codes and standards

In this approach, the reliability level implicit in the existing deterministic codes and standards is first quantified by performing reliability analysis for a number of typical structures which are designed to the existing code requirements. The reliability level implicit in a code can then be taken as the target reliability for the design of structures in the future. This is one of the most widely used approaches for establishing target reliability levels. Most applications have been in the derivation of partial safety factors in limit state design codes to replace the older working stress codes for buildings, bridges and offshore structures.

This approach assumes that existing codes have satisfactory levels of safety. Current practice is believed to be safe because it has evolved over a considerable length of time and would have changed if designs of structures had resulted in frequent failure. However, current practice may be too far on the safe side in which case it is not optimal.

In recent years, studies have been carried out [150, 151] to quantify the reliability levels implicit in the bridge assessment standard BD 21/84 [152]. The lowest values of reliabilities obtained for the different bridge types over a range of parameter variations are shown in Table 23. Note that there are some differences in the parameter variations and the probability distributions of the variables used in the WS Atkins and Imperial College studies that would influence the reliability values.

From this table, it is clear that the current code provisions result in a wide variation in reliability values across different types of components and parameter variations. The resulting failure probabilities also seem to be very low. Some judgement would

therefore be required in choosing a target reliability value once the reliability values implicit in the current code provisions are quantified.

Bridge Component	Failure Mode	WS Atkins [150]		Imperial College [151]	
		P_f	β	P_f	β
RC Slab	Bending	10^{-9}	6.0	10^{-8}	5.7
	Shear	$<10^{-10}$	6.5	-	-
RC Beam + RC Slab	Bending	-	-	$<10^{-11}$	7.1
	Shear	-	-	-	-
Steel Girder + RC Slab	Bending	10^{-9}	6.0	10^{-6}	4.7
	Shear	10^{-6}	4.7	-	-
PSC Beam + RC Slab	Bending	$<10^{-12}$	8.0	-	-
	Shear	10^{-6}	4.7	-	-

Table 23 Annual Reliability Levels implicit in BD21/84

7.5.1.3 Economic optimisation

The probability of bridge failures can be reduced to a very low value by increasing the partial safety factors. However, this incurs high costs and is hence uneconomical. On the other hand, a high target failure probability would result in bridges failing frequently during service with the related consequences of loss of life, traffic disruption, repair/rebuilding costs, etc., which again would be undesirable. It is therefore important to set the target reliability level that is optimal according to all important criteria.

This would depend on its function, importance, initial construction costs and the consequences of its failure in terms of loss of life, injury, traffic disruption, repair/ rebuilding costs, and other economic losses. It is possible to calculate the optimal level of target probability of failure provided the value of the consequences of failure can be estimated although these are often difficult to calculate accurately.

The Nordic Committee on Building Regulations [153] recommends target failure probabilities dependent on the nature and the consequence of failure as in Table 24. Ductile failure provides adequate warning before the whole structure fails, allowing mitigating action to be taken, hence a higher probability of failure is acceptable.

	Failure Type					
Failure Consequence	Ductile with reserve strength		Ductile with no reserve strength		Brittle failure	
Not Serious	10^{-3}	3.09	10^{-4}	3.71	10^{-5}	4.27
Serious	10^{-4}	3.71	10^{-5}	4.27	10^{-6}	4.75
Very Serious	10^{-5}	4.27	10^{-6}	4.75	10^{-7}	5.20

Table 24 Target Reliabilities for Building Design in Nordic Countries [153]

Economic considerations are also important when setting target reliability levels for existing structures. The repair or strengthening of an existing structure can be considerably more expensive than the design of a new structure. Therefore, every effort should be made to minimise or avoid unnecessary strengthening without unduly increasing the risk to the public. This is evident in the development of the bridge assessment code used in Canada [154]. The annual target reliability used for assessment varies between 2.25 to 3.75 (or $P_f \approx 10^{-4}$ to 10^{-2}) depending on the nature of element failure, redundancy of the bridge and the level of inspection effort. In contrast, for the design of new bridges, a constant target reliability of 3.75 ($P_f = 10^{-4}$) is used. Similar approaches have been used in other application areas, such as offshore structures.

7.5.1.4 Recommendations for a target reliability

The decision concerning how to set a target reliability is obviously a difficult one and is an issue that has remained unresolved by structural reliability engineers for many years. The method adopted in this project still had not been agreed upon by the time I left WS Atkins in Autumn 1997. However, the most preferred method is a combination of economic optimisation and calibration to existing codes and standards. Calibration to existing codes and standards on its own is too conservative and removes much of the benefits gained from using structural reliability methods in the first place. Economic optimisation is too unconservative and does not account for the risk tolerance (or intolerance) of users and the local community. Economic optimisation can be made more acceptable if it accounts for more than economics, such as the more qualitative issues including company image, social and political impacts, etc. through multi-criteria decision methods. Any target reliability set by economic optimisation must be compared with those implicit in existing codes to understand how conservative or unconservative it is and whether or not that is acceptable.

7.5.2 Definition of a decision rationale

Once the change in reliability over time of each crossbeam has been calculated, that still does not answer the question of how to schedule the necessary repair works within the budget. A completely separate decision rationale must be developed to identify the best time to repair each crossbeam and feasibility of fitting such a schedule within the budget. Figure 16 shows a proposed rationale for solving this problem, which is discussed in more detail below:

The first task in evaluating each crossbeam is to determine the latest intervention date, based on the change in reliability over time and the target reliability as described in the previous section. It would also be possible to apply confidence limits to this date.

It may not always be possible to fit all crossbeams needing repair in a specific year into one year's budget, and some may have to be deferred to the next year. Because they will have gone beyond their target reliability at that stage, it will be necessary to introduce interim measures. Therefore, the crossbeams needing deferment should be those with the lowest consequence of deferment. These are the Group B crossbeams

defined in Figure 16. The Group B crossbeams should have the lowest probability of failure, the lowest consequences of failure and the lowest consequence of implementing interim measures. This can be calculated for each crossbeam as an expected utility of deferring repairs, $E(U)_{interim+repair(t+1)}$:

$$E(U)_{interim+repair(t+1)} = U(DCR) + U(CIM) + U(IIM) + P_f \times \left(U(CF) + U(IF)\right)$$

Equation 21

Where, U(DCR) = The utility of the Discounted Cost of Repair at time t+1

Where, $DCR = CR/r^{t+1}$

Where CR = The Cost of Repair (design, material, equipment and labour costs) at time t+1.

r = the assumed interest rate

U(CIM) = The utility of the Cost of Interim Measures (cost of labour, materials and equipment associated with propping or weight restrictions) until time t+1.

U(IIM) = The utility of the Impact of Interim Measures (traffic disruption, delays, impact on drivers and on local inhabitants) until time t+1.

P_f = The probability of the crossbeam failing before it is repaired

U(CF) = The utility of the Cost of Failure (discounted cost of rebuilding, design, material, equipment and labour costs) before time t+1.

U(IF) = The utility of the Impacts of Failure (loss of life and injury, traffic disruption, delays, its impact on drivers and on local inhabitants, due to failure) before time t+1.

In some cases, the discounted cost of repair may give preference to deferring a crossbeam by one year. This would increase its priority for deferment, but in the overall interests of safety, if the budgets allowed, this crossbeam should still be repaired this year. Interim measures are still not as safe as carrying out a full repair. It may help to re-inspect any crossbeams that are to be deferred to update the predicted reliability before interim measures are designed.

In other situations, all crossbeams needing repair in this year may be catered for with funds to spare, in which case the next most important group of crossbeams can be examined and prioritised. This is Group C crossbeams in Figure 16. These crossbeams have not yet reached their target reliability but are in a condition that is more efficient to repair now than to delay until the target reliability is reached. In other words the total expected utility of carrying out repairs now is less that the total expected utility of carrying out repairs at year n, where n is the latest intervention date: $E(U)_{interim+repair(t+n)} > E(U)_{repair(t)}$ such that:

$$E(U)_{interim+repair(t+n)} = U(DCR) + U(CIM) + U(IIM) + P_f \times \left(U(CF) + U(IF)\right)$$

Equation 22

Where, U(DCR) = The utility of the Discounted Cost of Repair at time t+n

U(CIM) = The utility of the Cost of Interim Measures until time t+n

U(IIM) = The utility of the Impact of Interim Measures until time t+n

P_f = The probability of the crossbeam failing before it is repaired at time t+n

U(CF) = The utility of the Cost of Failure before time t+n

U(IF) = The utility of the Impacts of Failure before time t+n

$$E(U)_{repair(t)} = U(CR) + P_f \times \left(U(CF) + U(IF)\right)$$

Equation 23

Where, U(CR) = The Cost of Repair at time t

P_f = The probability of the crossbeam failing before it is repaired at time t

U(CF) = The utility of the Cost of Failure before time t.

U(IF) = The utility of the Impacts of Failure before time t.

The ratio of $E(U)_{repair(t)}$ / $E(U)_{interim+repair(t+n)}$ can be calculated for all crossbeams in Group C, and the crossbeams with the lowest ratio can be brought forward into the current year. However, there is little benefit in bringing forward any other crossbeams if funds remain. Any remaining crossbeams have an expected utility of repair at the latest intervention date lower than the expected utility of repair now. Of course, in real life, the number of crossbeams needing repair exceeds the budget, making this an unlikely situation.

I developed this decision rationale independently of WS Atkins after I had left their employment. However, I have since discovered that the methodology, which they applied, was very similar. Firstly, a target reliability level was agreed between the decision makers, which gave the latest date by which each crossbeam should be repaired. This latest intervention was between the present time and the next 60 years for all crossbeams assessed. All crossbeams that were predicted to become critical within the next 5 years were then grouped into contracts for repair now. Whole life cost principles were then adopted to identify the best time to repair each of the remaining crossbeams, using the latest intervention date as a constraint.

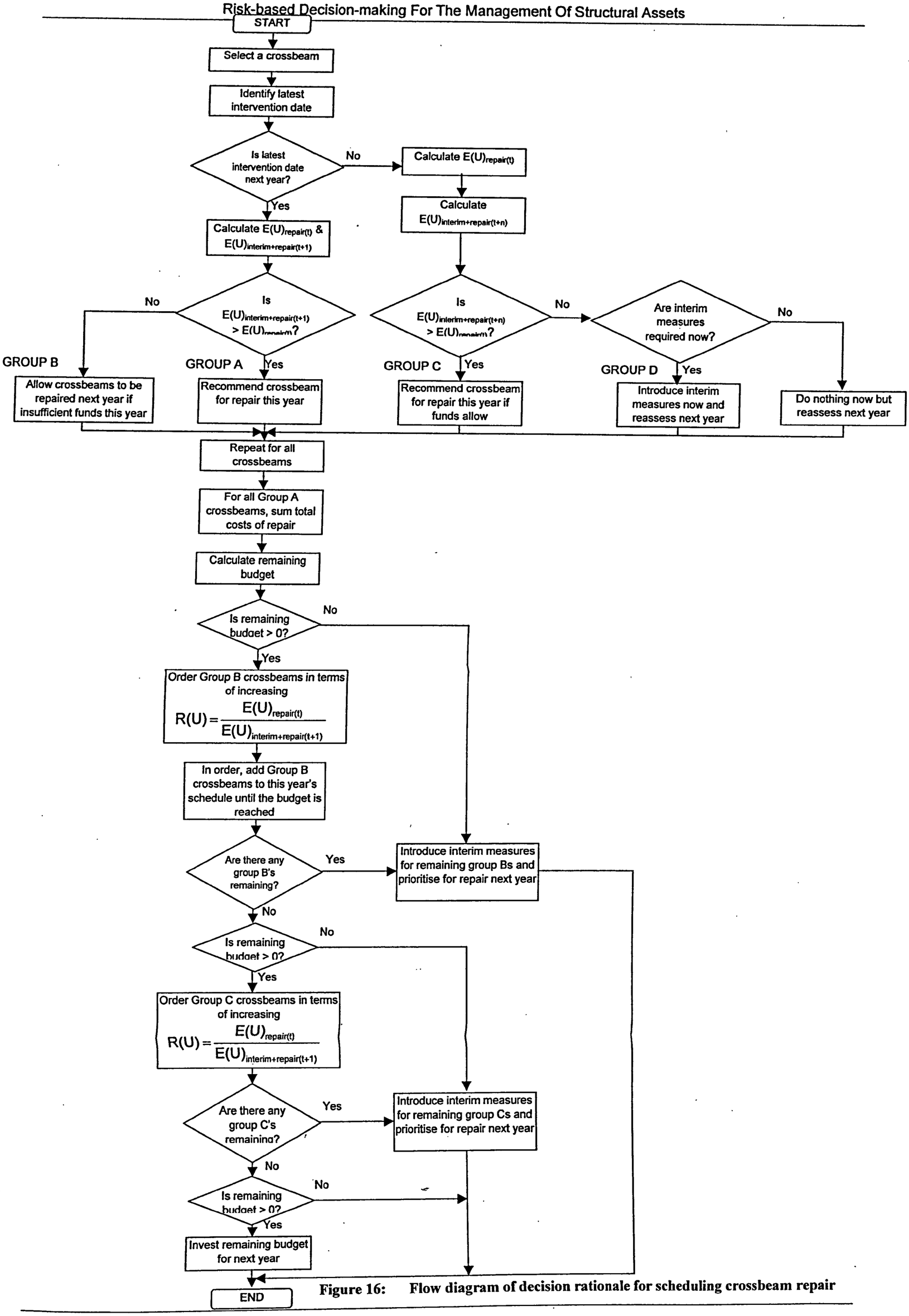


Figure 16: Flow diagram of decision rationale for scheduling crossbeam repair

7.6 Sensitivity Analysis

A number of sensitivity results are provided as output to a structural reliability analysis. These indicate the importance of the different parameters and their uncertainties to the reliability values calculated. This allows the decision-maker to refine the models and the parameter distributions to increase confidence in the decision made. The sensitivity factors show the relative importance (expressed as a percentage) of the uncertainty in each variable to the reliability index.

The elasticities of the mean values of the variables represent the change in reliability index due to a small change in the mean value of a variable (see Section 7.3.5 for definition). The elasticities are positive for those variables for which an increase in the mean value will increase the reliability of the component and will be negative for the other variables.

The elasticities of standard deviation for the limit-state of bending represent the change in reliability index due to a small change in the standard deviation of a variable (see Section 7.3.5 for definition). The elasticities for all the variables are negative because increasing the standard deviation (a measure of scatter or spread) of any variable will decrease the reliability of the component.

The following sections discuss the sensitivities for each failure mode and for three cases of the as-built condition, the present condition and the future condition. The actual graphs showing the results are presented in Appendix 4.

7.6.1 Flexure limit state

7.6.1.1 As-built condition

The sensitivity results for flexure, for the as-built condition of the crossbeam revealed that the reliability index is very sensitive to the uncertainty in bending moment due to the live load and the impact factor. The yield strength of longitudinal reinforcement and the uncertainties in the models used for load effect analysis and capacity of the component were also very important. Uncertainty in other variables, such as the concrete cube strength, effective depth, diameter of longitudinal steel and dead load did not have a significant influence on the probability of failure.

The elasticities of the mean values of bar diameter, yield strength of longitudinal reinforcement and effective depth of section were very important which is obvious for an under-reinforced section. The mean values of the analysis and capacity model parameters were also important.

The elasticities of standard deviation of live load bending moment, impact factor, yield strength of reinforcement and model uncertainty parameters were very important for reliability. These were much lower than the elasticities of the mean values of these variables. This implied that it is more important to determine the mean values of the parameters accurately than the standard deviation.

7.6.1.2 Present condition

A "Base Case" analysis was carried out for a high corrosion rate determined by a -390mV half-cell value. Additional parametric studies were then carried out for lower values of half-cell potential. The results of sensitivity factors from the Base Case analysis revealed that the uncertainty in the corrosion coefficient, was the single most dominant variable when the corrosion rate is high. The contributions of other variables became insignificant.

The elasticities of the mean values of bar diameter and corrosion coefficient were the most dominant. The yield strength of longitudinal reinforcement and the analysis and capacity model parameters were also important.

The elasticity of the standard deviation of the corrosion coefficient dominated the reliability of the crossbeam under bending.

In order to study the effect of different corrosion rates on the reliability of a crossbeam, reliability analyses were carried out for half-cell measurements ranging from -290mV (low corrosion rate) to -390mV (high). The sensitivity results for the low half-cell case were the same as those for the as-built case. In other words, the reliability is not sensitive to the corrosion parameters when the corrosion rate is low.

7.6.1.3 Future condition

The reliability of the crossbeam was also calculated at different points in time in the future. The results of sensitivity factors for the bending case corresponding to a "high" rate of corrosion showed that the uncertainty in the corrosion coefficient again dominated the crossbeam reliability. It was, however, found that, if the rate of corrosion was "low", the sensitivities were similar to those of the as-built condition.

The results of elasticities of the mean and the standard deviation showed a similar trend as was evident from the sensitivity factors. The elasticities were in general similar to the corresponding values for the present condition.

7.6.2 Shear limit state

7.6.2.1 As-built condition

The results of the sensitivity factors showed that the uncertainty in the capacity model dominated over all the other variables. The uncertainty in the analysis model and the impact factor were also very important. However, the uncertainty in concrete strength, yield strength of shear steel, live load effect and spacing of stirrups were less important.

The elasticities of the mean values of the resistance model and analysis model uncertainties were high compared to other variables. These parameters were significantly more important for shear than for bending. The elasticity of standard deviation of the resistance model was much higher than all the other variables.

7.6.2.2 Present condition

A "Base Case" analysis was carried out for a high corrosion rate determined by a -390mV half-cell potential. The results of sensitivity factors from the Base Case

analysis showed that the uncertainty in corrosion rate for shear had a dominating influence on reliability for a high corrosion situation. The contribution from other variables became insignificant.

The elasticities of the mean values of the resistance model and analysis model uncertainty were high compared to other variables. Also significant were the mean values of the area of shear steel and the corrosion rate of shear steel. The elasticity of the standard deviation of the corrosion rate of shear steel dominated.

In order to study the effect of different corrosion rates on the reliability of a crossbeam, analyses were carried out for half-cell values ranging from -290mV (low) to -390mV (high). The sensitivity results for the lower levels of half-cell showed that the uncertainty in the corrosion rate had no influence on reliability in a low corrosion situation. The results were sensitive to the same uncertainties as for the as-built case. .

7.6.2.3 Future condition

The reliability of the crossbeam at different points in time in the future was calculated for the shear limit-state. The results of sensitivity factors corresponding to a "high" rate of corrosion over a 10-year period, showed the same trend as that of the present condition. The importance of the corrosion coefficient for shear steel was dominant for the high corrosion rate case and insignificant for the low corrosion rate case.

The results of elasticities of the mean and the standard deviation showed a similar trend as was evident from the sensitivity factors. The elasticities were in general similar to the corresponding values for the present condition.

7.6.3 Bond limit state

7.6.3.1 As-built condition

The results of sensitivity factors reflected those for the flexure limit state. This was because, in the as built condition, all the reinforcement bars developed their full tensile capacity and the failure mode was essentially one of flexure failure.

The elasticities of the mean values of the yield strength of main reinforcement, the load effect analysis model and the diameter of the bars were high compared to other variables.

The elasticities of the standard deviations of live load bending moment, impact factor, yield strength of reinforcement and model uncertainty parameters were found to be very important.

7.6.3.2 Present condition

The results of sensitivity factors for the case with "high" corrosion rate, showed that the reliability of the crossbeam was completely dominated by the uncertainty in corrosion rate. Because of a high loss of area of reinforcement, the tensile capacity of the bars was lower than their bond capacity (i.e. resistance to slip), and hence the failure mode was one of flexure.

The elasticities of the mean values and standard deviations of variables were also similar to those of the flexure case in the present condition.

The sensitivity results for a low corrosion rate (-290mV half cell) and an initial delamination over 30% of the anchorage showed that the important variables were similar to those for bending failure. The concrete strength and the bond coefficient, β also showed a significant influence.

The effect of high initial delamination was studied by considering the anchorage zone to be fully delaminated in its present condition. The sensitivity results found that the most important variables were the factor η on delaminated bond strength, the bond coefficient β and the concrete cube strength. From this it was clear that the capacity of the bars in the fully delaminated condition was limited by their bond strength and the failure was likely to occur by slipping of the bars.

7.6.3.3 Future condition

The reliability of the crossbeam at different points in time in the future was studied for the bond limit-state. It was observed that the sensitivities changed depending on the governing mode of failure.

In the case of high corrosion rate (over a 10 year period), the failure type was bending and hence the reliability was governed by the uncertainty in corrosion rate. If, however, the rate of corrosion was "low", the sensitivity to the uncertainty in the delamination rate became the most significant. The uncertainties in the β coefficient and the η factor on delaminated bond strength also became significant. The results of elasticities of the mean and the standard deviation showed a similar trend as was evident from the sensitivity factors. The elasticities were in general similar to the corresponding values for the present condition.

Examination of the sensitivity factors showed that, for the "moderate" and "high" corrosion rate cases, the failure was one of flexure type and hence the variation of reliability with time was also similar to that of the flexure limit state. However, when the corrosion rate was "low", the sensitivities change markedly with time as the failure mode changed from flexure to bond. The importance of yield strength and impact factor reduced once the failure mode changed from flexure to bond.

7.7 Conclusions

The key problem addressed by this case study was not whether to repair certain crossbeams or even when to repair them so much as which should be carried out first. A set budget was available for the work, which was going to be spent, but the important question was on which crossbeams. The uncertainties and the consequences of the selection decision were significant and severe in terms of the loss of life that could result from the failure of the crossbeam. This meant that the decision had to be made as carefully and thoroughly as possible.

Due to the number of uncertainties involved, it was considered possible that a bridge component could fail from an adverse combination of extreme values of these variables.

These uncertainties arise from the inherent variability of loads and material resistance parameters, deterioration of bridge components over time, analysis models used for determining the load effects and capacities, and in measurement and inspection techniques. In order to decide when and how repair should be carried out, it was therefore necessary to consider the risk of the crossbeam failing, whether repair or maintenance is carried out or not. The risk was defined as:

Risk = Probability of failure * Consequence of failure

However, in this study, due to the consequences of crossbeam failure being approximately the same for all crossbeams, the probability of failure, only, was considered. In the current codes for design or assessment, using a number of partial safety factors to guard against extreme variations of the variables ensures the safety of a bridge component. However, structural reliability analysis methods were introduced to attempt to treat, in a rational manner, the various sources of uncertainties involved in a design or assessment process. In the reliability analysis, the partial factors were not used. Instead, the uncertain parameters were modelled using appropriate probability distribution functions and the probability of failure of the crossbeam was calculated.

For each limit-state (or failure mode) of the crossbeam, a separate reliability analysis was carried out to evaluate the probability that this limit-state will not be reached. These results were then combined to calculate the overall reliability of the component.

The resistance of the crossbeam was evaluated as a function of the uncertain material parameters (e.g. strength of concrete, yield strength of reinforcement, etc.) and geometrical parameters (e.g. effective depth, area of steel, etc.), which were considered as random basic variables and described using appropriate probability distributions. On the loading side, the dead load and the traffic load were treated as random variables. In addition, variables were introduced to model the uncertainty in the capacity calculations and in the analysis method used for calculating the load effects.

Stakeholders were initially expected to be an issue due to the importance of the road network and the extremity of the risks. However, it soon became clear that for all parties maximising safety was the primary criteria. This removed any serious conflict of interests and allowed focus to be placed on ensuring a robust evaluation of safety.

The set of basic alternatives was not difficult to identify as this covered all the crossbeams in the road network. The more difficult task in identifying alternatives involved considering how the different crossbeams could be combined into common repair packages to maximise the use of the budget and minimise traffic disruption. This was such a complex issue that a further process was developed beyond the risk-based decision model to formalise a structured approach.

The most important decision criterion was the safety of the road network. Due to the significant uncertainties and the severe consequences of failure, all parties considered any crossbeam failure intolerable. This meant the risk analysis became the focus of the decision process such that the most dangerous crossbeams should be addressed first. Because of the importance of the risk as the basis for the decision-making, it was

essential that a thorough understanding of the risk and its evaluation be gained. Other factors that still had to be taken into account but more as secondary issues were using the budget the most efficiently and minimising the disruption to traffic.

A decision analysis tree was constructed to try to gain increased understanding of the decision problem. However, the problem was far too complex for this simple method to bring much benefit. Therefore, a more detailed structural assessment was carried out by developing a decision rationale that would consider all of the important factors in the best context. The ability and opportunity to carry out such a detailed assessment of the decision issues within the risk-based decision model shows the flexibility of the model. It also proves its role as a guideline to support decision-making rather than dictate decision-making.

The information necessary to evaluate the risks as a basis for the decision-making was determined primarily from developing the structural reliability models. The main data was gathered from historical inspection reports and test data. Preliminary structural reliability analyses allowed the sensitivity of the results to the parameter uncertainties to be evaluated. This highlighted areas where further information would be beneficial.

The most important risk identified in this decision problem was the risk of any of the crossbeams failing before it could be repaired with catastrophic consequences. Because of the severe nature of the consequences, it was considered essential that the risks be quantified as clearly as possible. For this reason, detailed structural reliability analysis was carried out. The problem with structural reliability analysis however is what to do with the result. The probability of failure is not a very useful figure if there is not a maximum acceptable probability of failure to compare it with. Therefore, by establishing a maximum acceptable probability it was then possible to determine when each crossbeam was likely to pass that limit. This was then a constraint on the timing of when to repair the crossbeam. In this way, the risk assessment of each of the crossbeams was a direct input into the decision of when to repair. Such a detailed assessment of the probability of failure was appropriate to the problem because of the extreme importance placed on the results of the analysis.

The only preference formally accounted for in the decision-making process was the unanimous preference for minimising the risk of crossbeam failure. This was therefore incorporated into the decision by being the main decision criterion. The development of the detailed decision rationale was then used to show clearly the process by which the decision was made to build consensus and provide an audit trail for future reference. By carrying out the risk assessment and developing the decision rationale as an independent third party, it was possible to show impartiality to the decision process, which helped build confidence and ownership of the results by the stakeholders. This was especially the case in the risk assessment as there was some scepticism amongst stakeholders that risk assessments could be tampered with to give the result the decision-maker was looking for.

Following completion of this work, after I had left WS Atkins, the repair schedule that was finally recommended was adopted fully by the decision-makers. The decision-

makers found the support provided by the evaluation of such a complex decision to be extremely useful. They welcomed any support to give structure and meaning to the way in which this problem was solved.

The main area that was important to carry out sensitivity analysis in this case was in the uncertainties of the parameters in the structural reliability assessment. The uncertainties were so significant in some parameters that it was important to establish their effect on the risk assessment results. This then gave the opportunity to gather more data and/or refine the engineering models as necessary. As there were no conflicting preferences accounted for in the decision, it was not necessary to establish their sensitivity.

The use of the risk-based decision model to support this decision did not mean the introduction of risk analysis where it would not have normally been carried out. This was because it had already been decided that the risk of failure was the main issue. However, the risk-based decision model helped the decision-makers gain a clearer understanding of how to integrate the risk analysis results into the decision-making.

This case study has clearly demonstrated that rigorous reliability analysis procedures can be developed and applied to the assessment of viaduct crossbeams. It has also shown that risk-based decision methods provide significant support to the way that scheduling maintenance decisions are made under such conditions of uncertainty and limited budgets. The sensitivity factors presented also provided considerable insight into the failure behaviour of deteriorating crossbeams and identified the relative importance of different variables to the reliability of the crossbeam.

The decision problem addressed in this case was very heavily biased to risk assessment rather than any other aspect of decision-making. Furthermore, the decision model was not found thorough enough to give the recommended best option without further work, such as the development of a detailed decision rationale. However, if the model was more detailed then it would be too cumbersome for the more straightforward decisions. The model was still found to be very useful to ensure that all aspects of the decision were considered and evaluated and provided opportunities for the more detailed analyses to be carried out.

The application of the risk-based decision model to this case study ensured that all aspects of the situation were considered. For example, in engineering decisions it is often very easy to forget to consider stakeholder issues (as is the case of the Brent Spar problem for Shell). By using the model, a conscious decision had to be made whether to formally address all stakeholders or not. In this case it was decided that it was not necessary but that did not mean that it was a waste of time. Instead, it provided a clearly argued case to be used in defence of the decision should there be any problems at a later stage. The use of the decision model also helped identify the role of the risk analysis in the decision and how to use its results.

The use of a structured decision process to support the decision in this case helped the decision-makers identify the key issues to be addressed and the issues, which did not need to be addressed. It allowed the role of the risk analysis in the decision-making to

be clearly defined and the detail of analysis to be agreed upon. The use of the risk-based decision model brought the significance of the risks to the fore and meant that the assessment of risks was an integral part of the decision process. The clear structure of the decision process promoted understanding and ownership of the way the decision was made, which gave support for the results that were implemented. In addition, as a government related organisation it provided the decision-makers with an audit trail to show the logic and thoroughness of the decision-making in case anything went wrong at a later stage.

8 CASE STUDY 3

PLANNING OF PIPELINE REPAIR AND REPLACEMENT SCHEDULES

8.1 Problem Definition

8.1.1 Identify problem or opportunity

Corrosion was found to have occurred in a client's main oil pipelines. However, the client preferred to avoid leaks by proactive repair or replacement of corroded pipelines. We were requested to perform a remnant life assessment (RLA) study of the field's two 30" diameter main oil lines including the development of remnant life prediction software. This was then to be the basis for the ensuing decisions of how to optimise the extent and timing of repair or replacement for each pipeline.

In the early part of year 29, the oil lines had been adapted to be able to take an intelligent PIG (Pipeline Inspection Gauge) for internal inspection. A Magnetic Flux Leakage PIG was used at the end of Year 29 to measure remnant wall thickness throughout the pipeline. The results of the inspection indicated significant areas of grooving corrosion characteristic of carbonic acid corrosion and localised pitting corrosion. Because of this, the client reduced the Maximum Allowable Operating Pressure (MAOP) from 1050 to 980 psig and set up a monitoring and inspecting schedule for the worst locations to ensure pipeline integrity at least every two years.

In Years 30 and 31 external ultrasonic scans were carried out over localised areas of the pipe to monitor the worst areas of corrosion identified so far. In Year 32, another PIG inspection was carried out, this time an ultrasonic PIG was used. This survey also identified laminations and blistering characteristic of hydrogen-induced cracking (HIC).

It was therefore necessary to calculate the current capacity of the pipeline to ensure its current safety and the to determine the corrosion rate to which the pipeline was still subject to evaluate the remnant safe life of the pipeline. Once the remnant life was calculated it would then possible to use this information to rationally determine whether the pipeline should be repaired or replaced and when this should take place.

8.1.2 Identify stakeholders in the decision

Due to the significance of these oil lines to the production ability and capacity of the field (between 250 000 and 350 000 barrels per day) and due to the regional policy of zero tolerance to leaks, the decision to be made was significant to several groups of stakeholders. The decision, after all, had to be seen to minimise the capital and operational expenditure, the probability and consequence of lost production, the probability and consequence of any leaks. These consequences were in terms of costs, impacts on the environment, shareholders, and revenue.

One of the first stages in the analysis, therefore, was to determine who was in the decision-making group and the extent each could and wanted to, influence the decision.

8.1.2.1 The external stakeholders

The external stakeholders in this decision problem were identified to include users of the end product, environmental pressure groups and government officials.

8.1.2.2 The internal stakeholders

The internal stakeholders were identified as the asset manager and the asset management group members. The asset manager, responsible for the asset's day-to-day operation was the head of the client company's Quality Assurance department.

The asset management group was the shareholder's board, responsible for allocating annual budgets for each asset. However, different shareholder groups were responsible for different budgets. The national oil company, who were majority shareholders in the client company were responsible for the operational and maintenance budget. However, any requirement for capital expenditure, had to be funded by both shareholder groups. This meant that around 40% of the shareholders wanted to avoid any capital expenditure, while the other 60% wanted to distribute the costs and therefore preferred capital expenditure to operational expenditure. Because of these strongly held preferences, it was important, for the client to cut through any politics and ensure the "best" decision was made, to ensure the maximum safety and productivity of the pipelines, while minimising total costs.

Due to these politics the decision strategy for recommending repair or replacement was believed to be less important than determining the acceptability of the risk. However, a rational assessment of the decision alternatives would provide a sound case to support the final recommendation and encourage consensus between shareholders.

8.1.3 Identify viable alternatives

This decision's alternatives involved selecting whether to repair the pipelines at the most corroded locations or to replace them. The key issues, therefore, were identifying and selecting the most important repair locations and judging the best repair time.

8.1.4 Formulate decision objectives and criteria

The decision-makers did not explicitly articulate the decision criteria as the politics were too strong. However different criteria were inferred from discussions with the two main stakeholder groups. For the majority shareholders, responsible for the operational costs of the pipeline, the main decision criteria were in order of importance:

- The safety of the pipeline
- The total cost of operating the pipeline for the remaining life of the field (i.e. including operational and capital expenditure.
- The probability and consequence of lost production due to shutting down the pipeline.

For the minority shareholders, only responsible for the capital costs associated with the pipeline, the main decision criteria were in order of importance:

- The safety of the pipeline
- Minimal capital expenditure on the pipeline for the remaining life of the field.
- The probability and consequence of lost production due to shutting down the pipeline.

There was obviously conflict between the two stakeholder groups, and therefore it was necessary to build consensus. It was decided to base this on the criteria on which the two groups agreed, i.e. safety and productivity of the pipeline. In utility analysis (described later), these would receive the highest weightings as they were most important to most people. In this case, the pipeline safety was by far the most dominant criterion. Due to the time schedule for this project, the focus of the work was therefore, on the risk-based corrosion assessment of the pipelines to allow an evaluation of the remnant life. Due to the client's zero leak tolerance, any consequences of failure were deemed unacceptable, therefore only the probability of failure was calculated.

8.2 Structural Analysis

The structuring process supports the decision-maker in identifying all possible alternatives and outcomes, and to see all the decision paths open to him. Either a decision tree or an influence diagram can represent these. Although decision trees are most useful for tackling complex, sequential problems, they can also be useful for structuring simple ones. Figure 17 shows a decision tree for this decision problem.

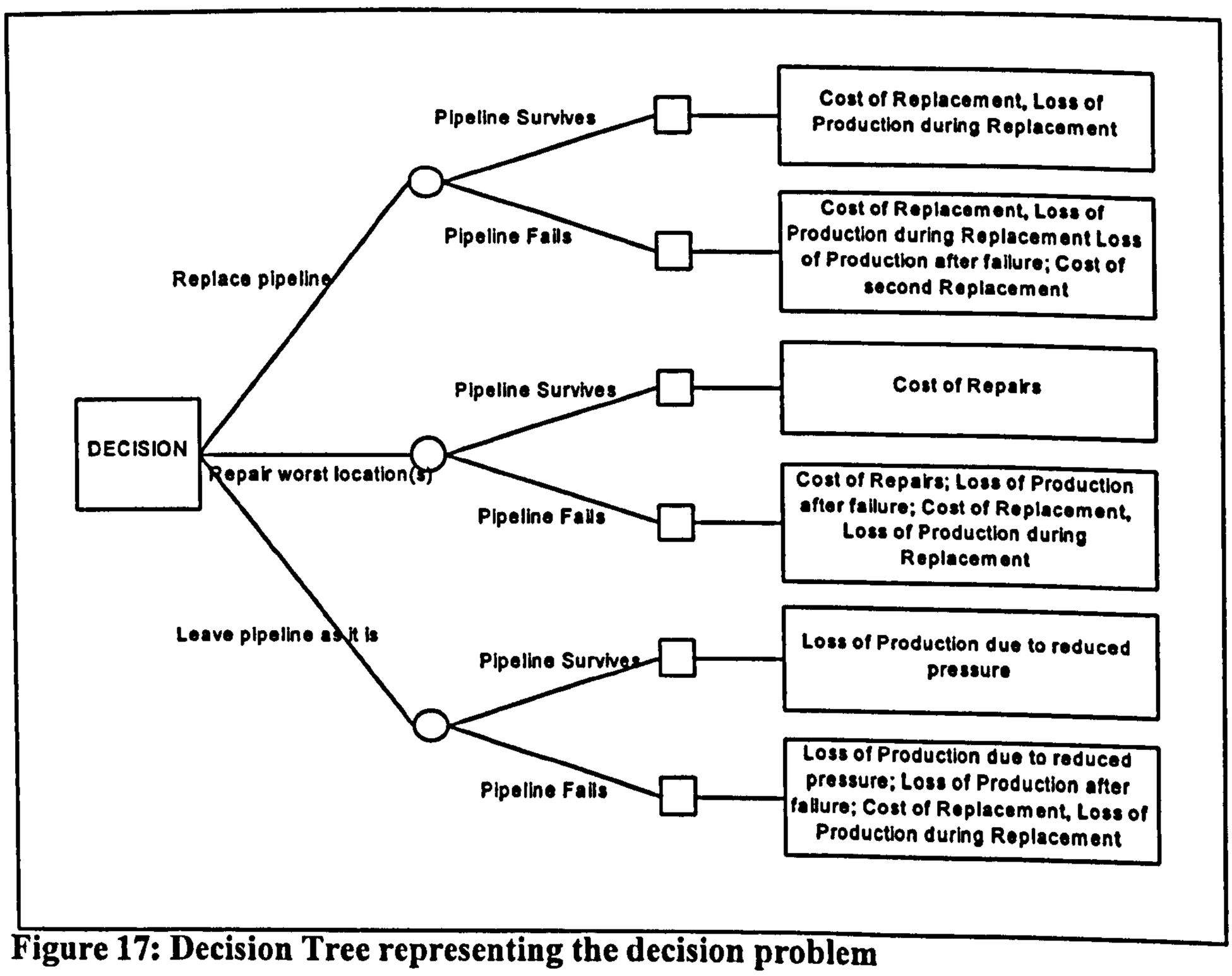


Figure 17: Decision Tree representing the decision problem

8.3 Uncertainty and Probabilistic Analysis

The changes in inspection technology and hence in the preferred methods for and accuracy of surveys make it difficult to reconcile different sets of inspection results taken over the pipeline's lifetime. Sometimes earlier data may be ignored to rely on the findings of later inspections. The difficulty, therefore, lies in establishing a comprehensive framework within which the results from a number of disparate inspection campaigns can be properly reconciled while taking into account all the uncertainties associated with the pipeline condition. The method developed in this case study allows all the relevant inspection results to be analysed holistically, ensuring that optimal use is made of all available inspection data.

The approach developed takes account of all sources of uncertainty associated with pipeline corrosion rate prediction. These include large-scale factors (transported fluid corrosivity and inhibition effectiveness), medium scale factors (temperature, pressure, flow regime) and small-scale factors (local pitting and inspection data uncertainties).

The methodology was developed to allow continuous updating of corrosion predictions based on all available information including results from further general and local spot inspections, leak data, and knowledge of no leaks at any time. The resulting corrosion predictions are therefore always consistent with the known pipeline conditions.

The assessment is based on the quantitative results of wall thickness measurements obtained through two internal intelligent pig inspection surveys. The first (magnetic flux) intelligent pig inspection was undertaken in Year 29. This survey reported approximately 32000 individual metal loss features having a depth in excess of 10% of wall thickness. The second (ultrasonic) pig inspection was undertaken in Year 32. This survey reported approximately 4000 individual internal metal loss features. The significant reduction in the number of individual features reported results from the accretion of many small defects into a smaller number of larger defects with more complex morphologies both through the way the defects were defined and through increased corrosion. In order to overcome the problem of inconsistent defect definition and reporting, it was necessary to obtain the basic metal loss data in matrix format. This allowed the re-definition of the defects in a consistent manner.

8.3.1 Corrosion prediction

The survey results revealed that significant corrosion was ongoing throughout the length of the two oil lines. The most severe metal loss defects were clustered within the first pipeline. Three sections (2, 4, and 6) of the second pipeline also showed a significantly higher density of metal loss defects than the within this pipeline as a whole.

Pipeline 1 had a negligible flow rate, resulting in near stagnant conditions with significant water dropout. Corrosion inhibition was not expected to be effective in this pipeline, and the high levels of metal loss in this location were therefore as expected. Analysis of the Year 29 and Year 32 intelligent pig data revealed local corrosion rates of up to 1.6 mm/year (average corrosion rate between surveys).

In Section 1 of Pipeline 2 the flow velocities were high enough to prevent water dropout at typical production rates therefore corrosion conditions were only expected during periods of low flow rate. The results of the Year 32 intelligent pig survey supported this hypothesis. Beyond the start of Section 2 both the flow regime in pipeline 2 downstream of the start of section 2 was intermittent (slugging two-phase flow) at all flow rates considered and corrosion conditions were therefore expected to occur frequently downstream of this location. The results of the Year 32 intelligent pig survey showed that the frequency of defects and corrosion rate did increase, and some defects had depths approaching those found in Pipeline 1. These variations were believed to be due to the local flow regimes in different parts of the pipeline.

8.3.1.1 Hydrogen induced cracking

Hydrogen Induced Cracking (HIC) was reported throughout the length of both pipelines. Both planar and bulging laminations were identified throughout the pipelines. External ultrasonic inspection identified that some laminations include a radial component indicative of the presence of stepwise cracking (which can form a leak path).

It is difficult to draw precise conclusions about the time at which HIC occurred. Evidence from the surveys showed that at least one metal loss defect associated with a burst lamination was present at the time of the Year 29 survey. HIC can progress very rapidly when conditions favour it and may then be stabilised for long periods.

HIC is driven by the diffusion of atomic hydrogen into the pipe wall. Atomic hydrogen is expected to be present in the system because of ongoing corrosion in the presence of H_2S. It is therefore considered probable that the HIC is ongoing.

HIC threatens the integrity of the pipeline in two ways. Firstly through the development of through wall leak paths as a result of stepwise cracking, secondly through the rapid formation of very large metal-loss features caused by the "bursting" of one or more blisters in a heavily blistered area of the pipe.

HIC crack propagation does not proceed at a constant rate and it can be arrested completely before increasing again at an exponential rate. On this basis, the assessment of HIC type defects can only be performed on an "as-observed" basis as any prediction of future defect size and shape cannot be made with any degree of confidence.

8.3.1.2 Corrosion modelling

A predictive model for steel corrosion was developed by APA based on three corrosion models developed by de Waard, Lotz and Dugstad [155], de Waard and Lotz [156] and NORSOK [157], to take into account the combined effects of carbonic acid and hydrogen sulphide. These models were chosen because grooving corrosion attributed to carbonic acid was identified in the pipeline. All these models had been empirically developed. A number of correction factors were applied to these models to account for the effects of:

- Non-ideality of the gas
- H_2S partial pressure on the fluid pH

- Formation water chemistry on the fluid pH
- The dependence of Henry's constant on the dissolved solids in the formation water

In addition, of the likelihood of preferential oil wetting of the pipe wall was assessed.

8.3.1.3 Comparison of calculated with observed corrosion rates

The process conditions in the pipe were simulated using HYSYS commercial software. The predicted general corrosion rates for these analyses are shown in Table 25. These predictions compared well against observed general corrosion rates of 0.2 to 0.3 mm/yr. The general corrosion rate was seen to be further accelerated due to pitting corrosion.

Model	Predicted Corrosion Rate (mm/yr)	
	Case 1	Case 2
De Waard 93	0.20	0.21
De Waard 95 Note 1	0.10	0.10
NORSOK M506 Note 2	0.27	0.26

Table 25 Corrosion Modelling Results

Note 1. Flow velocity is below applicable range and therefore corrosion rate is underestimated

Note 2. Shear stress is below applicable range, however, at low values the corrosion rate is relatively insensitive to this parameter and is therefore not significantly underestimated.

The increased pitting corrosion rate observed at the individual defects identified by the intelligent pig surveys is determined by the remnant life software, described below, by factoring the general corrosion rate by an observed pitting rate.

8.3.2 Basis of remnant life analysis for the oil lines

The corrosion models described above were used with predicted process conditions within each pipe joint to determine a corrosion rate. The analyses assumed homogeneity of both the fluid and the steel substrate and therefore did not assess local factors such as the breakdown of inhibitor films, flow variations, metallurgical variations in the steel and fluid conditions within a pit. These factors result in a distribution of corrosion rates under identical global conditions and lead to the corrosion morphology actually seen.

The remnant life assessment software described here, addresses these factors by modifying the global corrosion rate by a "localisation factor" determined for each corrosion defect based on the comparison between the predicted corrosion rate and the inspection data. For a pit to develop, the local corrosion rate must be higher than the prevailing general rate, thus the inclusion of this factor ensures that the corrosion rate at individual features is not underestimated.

8.3.2.1 Survey accuracy

The two sets of intelligent pig results were obtained using significantly different instruments. This means that the accuracy of the measurements obtained during the surveys is also significantly different. Because of this, a major obstacle in the

assessment of the survey data is the reconciliation of the two sets of findings. The accuracy claimed by the operators of the two types of pig is presented in Table 26.

PIG type	General corrosion reporting threshold	Pitting corrosion reporting threshold	Measurements within confidence limit (%)	Measurement confidence limits	Implied standard deviation
Magnetic Flux	10% wall thickness	30% wall thickness	80%	± 10% wall thickness	1.038 mm (if wt=13.3mm)
Ultrasonic		20mm diameter base	95%	±0.5mm	0.255 mm

Table 26: Quantification of uncertainties associated with each PIG type.

8.3.2.2 Reconciliation of survey measurements

The survey estimates of wall thickness are subject to random errors as described above. For some defects, the difference between the observed remnant wall thickness at two surveys is small enough that the measurement error bands overlap. Assuming complete independence between the statistical distributions therefore, cannot be justified, as this would lead to the possibility that the wall thickness increased between surveys. To avoid this outcome it is necessary to reconcile each pair of wall thickness observations by updating the probability distributions for the measurement errors.

Each individual measurement was modelled as a normal distribution with a mean value equal to the observed value and a standard deviation appropriate to the survey technique. However, if the two measurements are considered together it is obvious that, irrespective of the actual values attributed to the measurements, the wall thickness for the first measurement must be equal to or greater than the wall thickness for the second measurement. The best estimates of the actual wall thicknesses at each survey are modified by the observed thicknesses and associated errors at the other survey.

In practice, the effect of reconciling the two sets of survey results is to increase the median corrosion rate over that predicted in a deterministic assessment. This increase is greatest where two measurements are close (i.e. where the overlap in the error distributions is greatest). Because the standard deviation of the later ultrasonic measurements is smaller than that of the early magnetic flux measurements, the remnant wall thickness estimates at the later survey are relatively unaffected by reconciliation.

The methodology used to reconcile the survey data uses a Monte Carlo simulation procedure to generate random wall thickness scenarios based on the survey data and the known uncertainties associated with the survey data. The random data sets representing the corrosion rate and wall thickness for each defect were then combined to create a set of scenarios for the progression of the corrosion at all defects considered.

8.3.2.3 Variations in operating conditions

Throughout a pipeline system, the occurrence of conditions required for corrosion (water wetting of the pipe wall) is dependent on both the flow velocity and flow regime. If flow velocities are high enough to prevent water dropout, corrosion will be negligible. If flow is slugging two-phase, corrosion conditions are expected. If flow rate is

negligible (near stagnant conditions), significant water dropout and hence corrosion will occur. Corrosion inhibition is the only protection against high levels of metal loss.

The corrosion rate prediction model, described above, was used to estimate both the historic cumulative general corrosion over a specified time interval and the predicted future corrosion rate under assumed operating conditions. The difference between the predicted average corrosion rate between intelligent pig surveys and the predicted future corrosion rate based on assumed future operating conditions was used to modify the predicted failure dates to account for changes in the transported fluids' corrosivity.

8.3.2.4 Availability of Corrosion Inhibition

An additional random distribution was introduced into the analysis to represent the corrosion inhibition availability from the date of the last survey forward into the future.

The corrosion inhibition availability must take a value between 0.0 and 1.0. For this reason, it was modelled using a Beta distribution with finite upper and lower tails. For the base case analysis, the Beta distribution parameters were selected to give a mean value of 0.9 and a standard deviation of 0.01. Modelling the inhibition availability as an uncertain quantity increases the variability of the calculated failure times. The small standard deviation was assumed to avoid an adverse influence on the base case assessment results. Modifying the appropriate parameters and repeating the analysis assesses the potential effects of higher or lower corrosion inhibition availability.

8.3.2.5 Determining the remnant life of the oil lines

For each scenario, (for this case study 3000 scenarios were considered) the date corresponding to either structural failure or through wall corrosion for each defect was determined. Once the failure dates were obtained, they were manipulated as follows:

- By ranking the dates of the failure of a single defect across all of the scenarios, an estimate of the probability of failure of any defect at any date could be derived.
- By selecting the earliest failure date from each scenario and then ranking them, the probability of the first failure of any defect at any date could be estimated.
- By selecting the nth date from each scenario and then ranking them, the probability that the nth defect failure has occurred by any specified date could be estimated.
- By excluding scenarios where one or more failures happen before a given date and reanalysing the remaining scenarios, the analysis was updated to reflect current knowledge of no failures.

8.3.2.6 Data used in analysis

An initial set of 30 defects with the smallest reported remnant wall thicknesses in the Year 32 ultrasonic intelligent pig survey were selected for the analysis. In order to establish the local corrosion rates effective between the dates of the two surveys it was necessary to establish the metal loss reported in the Year 29 survey at the corresponding location. Discrepancies in the reported locations between the two surveys meant that the Year 29 reported locations could not be used to identify the required wall thicknesses.

The process adopted involved comparison of pipe joint reported lengths to determine the equivalent pipe joint numbering for the two surveys and derivation of the distance of each reported defect from the start of the pipe joint in which it lies. For confidentiality reasons, the data on which this assessment was based cannot be presented.

8.3.2.7 Through wall corrosion of pipeline 1

Table 27 presents the results for Pipeline 1 in respect of through-wall corrosion. The analysis results indicate that the median estimate for the first leak date from the 30 defects considered here is the middle of Year 35. The 5% and 95% confidence limits for the first leak date are the end of Year 34 and the middle of Year 36 respectively. The table also shows equivalent dates for the predicted second to fifth leaks.

Probability	First Leak	Second Leak	Third Leak	Fourth Leak	Fifth Leak
5%	Month 10 Year 34	Month 4 Year 35	Month 8 Year 35	Month 11 Year 35	Month 3 Year 36
10%	Month 12 Year 34	Month 5 Year 35	Month 9 Year 35	Month 1 Year 36	Month 5 Year 36
25%	Month 3 Year 35	Month 9 Year 35	Month 1 Year 36	Month 5 Year 36	Month 9 Year 36
50%	**Month 7 Year 35**	**Month 1 Year 36**	**Month 5 Year 36**	**Month 9 Year 36**	**Month 1 Year 37**
75%	Month 12 Year 35	Month 5 Year 36	Month 10 Year 36	Month 3 Year 37	Month 7 Year 37
90%	Month 4 Year 36	Month 10 Year 36	Month 3 Year 37	Month 8 Year 37	Month 1 Year 38
95%	Month 6 Year 36	Month 1 Year 37	Month 6 Year 37	Month 11 Year 37	Month 5 Year 38

Table 27: Predicted Dates of Through Thickness Leaks for Pipeline 1 (30 defects)

Figure 18 shows the cumulative probability of through thickness corrosion for each of the 30 defects in Pipeline 1 plotted against time. The steepness of the curves indicates the corrosion rate associated with each individual defect. It is clear that there is significant variability between the median predictions of the through wall penetration date (i.e. Year 36 to Year 55). However, the Year 32 survey observed wall thicknesses cover a range of only 1.4 mm for all but one of the defects considered.

Figure 19 shows the probability of through thickness penetration for Pipeline 1 by one, two, three, four and five of the defects plotted against time.

Figure 20 shows the relative frequency for each of the defects of providing the initial through wall penetration. Defects 5 and 13 are dominant and together account for 55% of initial penetrations. An analysis of the differences between the Year 29 and Year 32 wall thicknesses showed that defects 5 and 13 are statistical outliers. This means that the observed reduction in wall thickness at these sites between Year 29 and Year 32 is significantly greater than would be expected based on the observations at the other 28 sites analysed. There is therefore evidence of inconsistency in the survey results at these two locations.

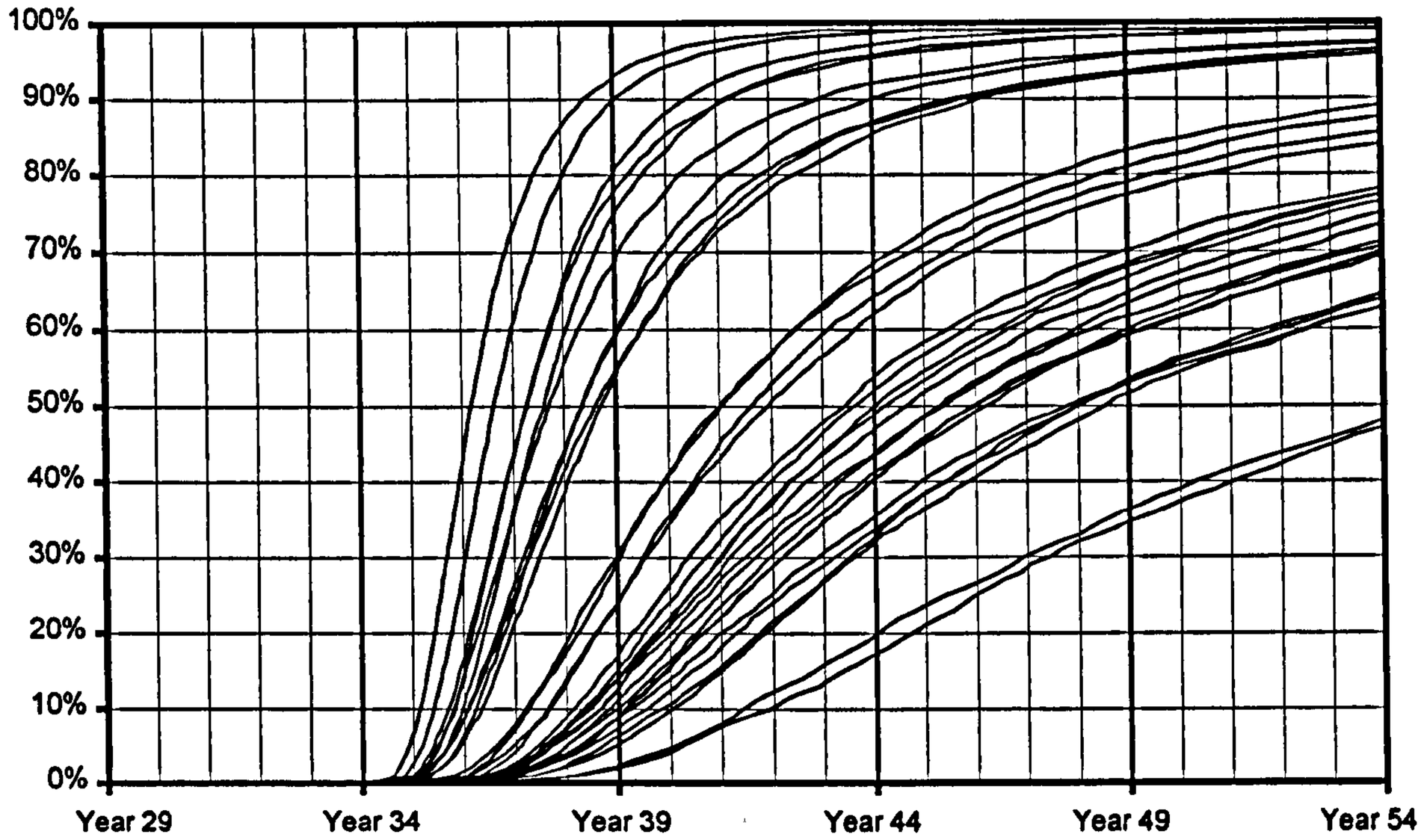


Figure 18 Probability of penetration for Pipeline 1, individual defects

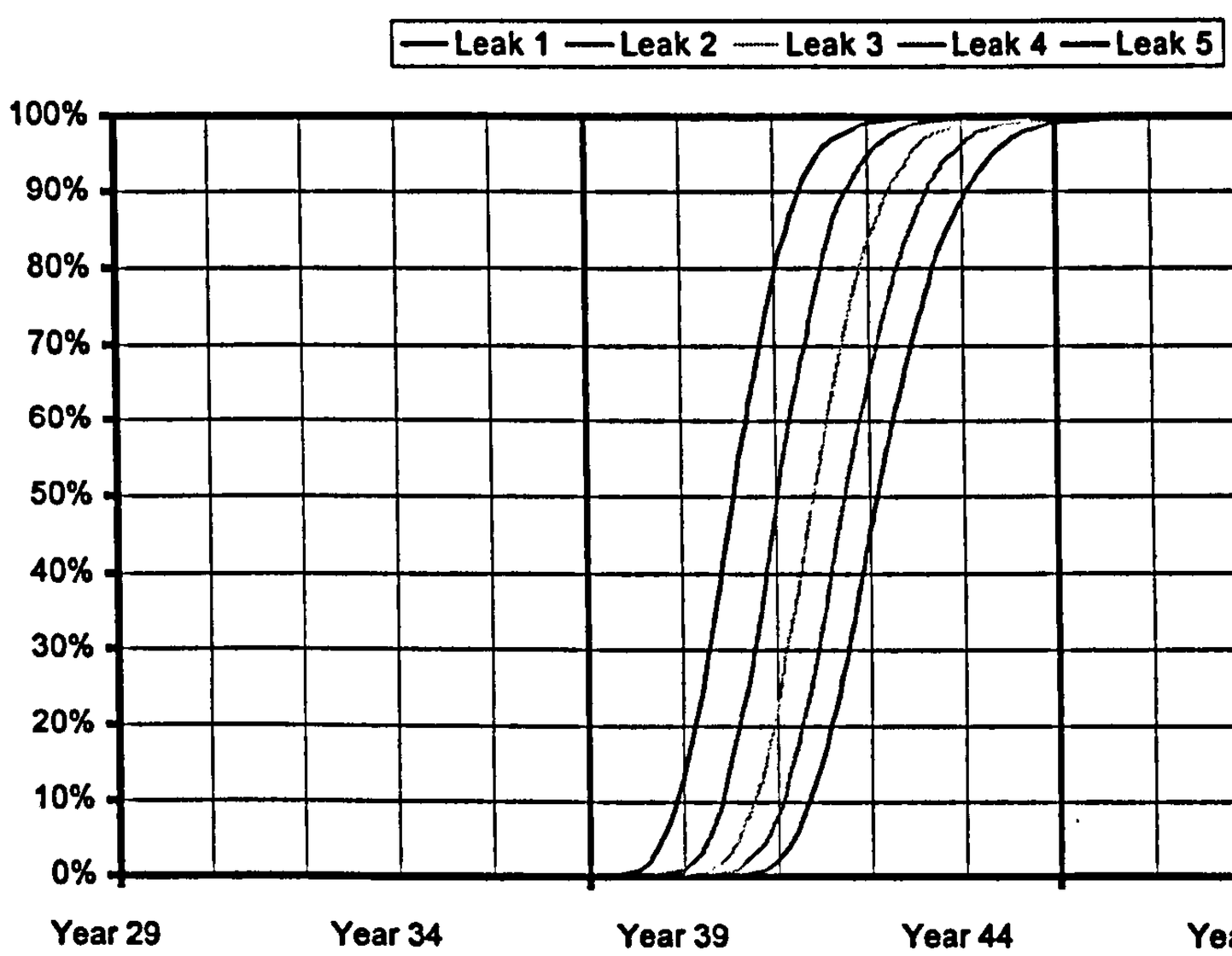


Figure 19 Probability of penetration for Pipeline 1, all defects

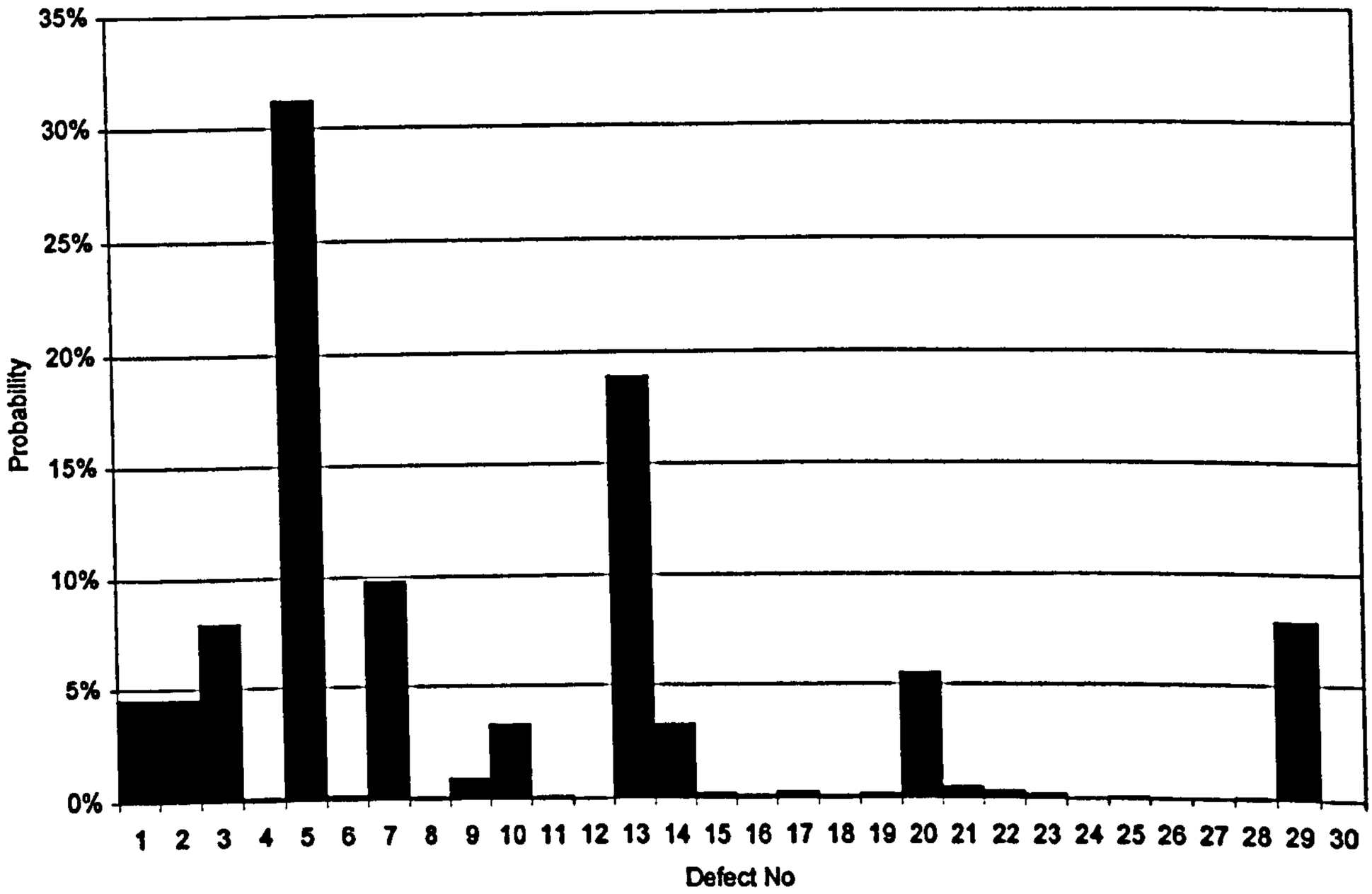


Figure 20 Relative Frequency of Initial Penetration for Pipeline 1

A sensitivity analysis of the results demonstrated that the analysis is relatively insensitive to the inclusion of these individual outlier defects (5 and 13). This is because within the sample considered, the defects all have approximately the same depth and corrosion rate. It is also due to the relatively large uncertainty in the observed corrosion rate, which is driven by the (relatively) large depth measurement uncertainty associated with MFL (magnetic flux leakage) inspection tools and the short time between the two surveys.

8.3.2.8 Failure of ligament of pipeline 1

The remnant life assessment described so far only considers through wall penetration of the defect and ignores the structural response of the defect ligament. In practice, the ligament may undergo structural failure before the defect penetrates through the full thickness. Whether or not this occurs depends on the state of stress in the pipeline and the criteria used to define failure.

The methodology presented in the ASME B31.8 Fitness for Purpose Appendix [158] was used. The value of MAOP (Maximum Allowable Operating Pressure) used to calculate the safe operating pressure was the original design MAOP. This should not be adjusted to account for any de-rating that may have occurred. It follows that the safe operating pressure incorporates the original hoop stress safety factor used in design. A factor of 1.1 represents the difference between the specified minimum yield stress (SMYS) and the assumed flow stress of the material. The criterion assumes that the pipe wall remains ductile. In order to use the criterion to assess remnant life three modifications are required:

- The assessment should be based on a realistic assessment of the actual operating pressure rather than on the MAOP, which may never be reached.
- The factor of safety implicit in the criterion must be removed.
- A realistic failure stress must be used.

Failure is defined as either when the stress calculated using the above formulation exceeds the hydrotest hoop stress or when the defect penetrates through thickness.

The remnant life was analysed using the same data as before. As expected, the predicted remnant life is shorter than that for through thickness corrosion only. The results are given in Table 28, with the predicted through thickness corrosion dates only.

Probability	Critical Ligament Stress	Through Thickness Penetration
5%	Month 9 Year 33	Month 10 Year 34
10%	Month 10 Year 33	Month 12 Year 34
25%	Month 1 Year 34	Month 3 Year 35
50%	**Month 3 Year 34**	**Month 7 Year 35**
75%	Month 7 Year 34	Month 12 Year 35
90%	Month 10 Year 34	Month 4 Year 36
95%	Month 1 Year 35	Month 6 Year 36

Table 28: Predicted Dates of Critical Ligament Stresses for Pipeline 1

8.3.2.9 Corrosion assessment of pipeline 2

Pipeline 2 was assessed section by section. The analysis performed was the same as that described above for Pipeline 1. The pipeline was sectioned into 6 sections as before for detailed analysis based on the local variations in metal loss frequency.

Within each section, the 30 locations having the deepest corrosion were analysed as described previously. The results of the analysis (expressed in terms of the date of through thickness corrosion and structural failure) are given in Table 29 and Table 30.

Section	Median Estimate	5% Confidence	95% Confidence
1	Month 7 Year 41	Month 7 Year 39	Month 3 Year 44
2	Month 1 Year 38	Month 3 Year 36	Month 6 Year 40
3	Month 5 Year 46	Month 10 Year 42	Month 3 Year 51
4	Month 9 Year 37	Month 6 Year 36	Month 4 Year 39
5	Month 1 Year 40	Month 3 Year 38	Month 5 Year 42
6	Month 10 Year 37	Month 5 Year 36	Month 4 Year 39

Table 29: Predicted Dates of Through Thickness Defect Penetration for Pipeline 2

As expected, when considering structural failure the estimated remnant life is less than when considering through thickness penetration only. It should be noted however that there is more uncertainty associated with the ligament failure estimates because they depend not only on the data obtained in the various surveys but also on assumptions about the pressure in the pipeline and the failure stress in the ligaments.

Section	Median Estimate	5% Confidence	95% Confidence
1	Month 11 Year 36	Month 9 Year 35	Month 4 Year 38
2	Month 8 Year 36	Month 4 Year 35	Month 1 Year 38
3	Month 3 Year 41	Month 7 Year 38	Month 6 Year 45
4	Month 10 Year 35	Month 1 Year 35	Month 9 Year 36
5	Month 8 Year 36	Month 5 Year 35	Month 1 Year 38
6	Month 5 Year 36	Month 1 Year 35	Month 3 Year 38

Table 30: Predicted Dates of Critical Ligament Stresses for Pipeline 2

8.3.3 Remnant life assessment conclusions

The conclusions of this analysis and the consequential recommendations were presented to the stakeholders as a basis for their decision-making. Pipeline 1 and three of the six sections of Pipeline 2 were expected to develop through thickness corrosion defects by the start of Year 38. Pipeline 1 and five of the six sections of Pipeline 2 were expected to develop critical ligament stresses, assuming a net internal pressure of 600 psi, at corrosion defects by the end of Year 36. Within Pipeline 1 and each of the sections of Pipeline 2 there were found to be a large number of defects having the potential to develop to through thickness penetration or to give rise to critical ligament stresses. Because of the large number of potential leak sites, the installation of clamps at critical sections was not considered to provide a practical means of long-term mitigation.

The client had stated that pipeline leakage could not be tolerated for safety, environmental and business reasons. In light of both the remnant life calculations and the effects of HIC on the pipeline, it was concluded that the condition of the two pipelines was not consistent with this stated aim. It was therefore recommended that two replacement (HIC resistant) pipelines should be installed as soon as possible.

It was further recommended that the MAOP should be reduced. Limiting the pipeline pressure would extend the remnant life with respect to the development of critical stresses. Through wall defect penetration would then govern. The pipelines currently operate at pressures significantly below the derated MAOP of 980 psi. It was believed that a further reduction in MAOP might be achievable without affecting operations.

Finally, it was recommended that intelligent pig inspections of the two pipelines should be undertaken every 18 months to 2 years until the pipelines are taken out of service.

8.4 Utility/Value Analysis

The results of such a remnant life assessment and the above recommendations obviously require a reaction. With a minimum remnant life in one location of only one year, it is necessary to make a decision to repair or replace the pipeline. Such a decision can be highly contentious and political with different stakeholders pushing for different outcomes. Any intuitive decision is very difficult to justify.

The use of utility analysis within a risk-based decision-making process allows alternatives to be considered by accounting for all consequences of failure such as the

loss of life, environmental damage or damage to company reputation in terms of a non-dimensional value. This accounts for:

- the decision maker's attitude to risk
- the value of the consequence in a convenient and meaningful dimension
- any non-linearity between actual value and the effect of the value on the organisation
- the relative importance of each factor to the stakeholders

The opportunity did not arise to implement such an analysis explicitly, however, following discussions with the stakeholders, it was possible to qualitatively identify their preferences. These then directed how the final decision was made.

As discussed in Section 8.1.2, the decision had to be seen to minimise capital and operational expenditure, the probability and consequence of any leaks and lost production. This decision problem was further complicated by the fact different shareholders were responsible for different budgets. This meant that approximately 40% of the shareholders were keen to avoid any capital expenditure, while the other 60% were keen to distribute the costs and therefore preferred capital expenditure to operational expenditure. Because of these strongly held preferences, it was important to cut through the politics and ensure the "best" decision was made, to ensure the maximum safety and productivity of the pipelines, while minimising total costs.

It was decided to base the consensus on the criteria on which the two groups agreed, i.e. safety and productivity of the pipeline. This was in line with the methods of utility analysis, as these criteria would have received the highest weightings as they were most important to most people. The order of preference for the criteria specified by both shareholder groups, was presented in section 8.1.4. This showed that the pipeline safety was given the most importance by both groups.

It therefore became clear that the governing decision factor, in the eyes of the identified stakeholders, was the probability of a leak. Therefore the results of the remnant life assessment showed very clearly that the probability of a leak in the two oil lines was significant and could not be ignored for very long. Furthermore, the number of leaks possible within the following couple of years meant that a program of repairs would not be cost effective. This meant that the minority shareholders were convinced that any proposal to repair the pipeline out of the maintenance budget was inefficient and highly risky, as the repair clamps proposed would not guarantee against a leak.

Based on the indisputable facts presented from this remnant life assessment the shareholders were, able to agree on a strategy to replace the pipeline as soon as possible. Currently the shareholders are putting together a strategy to replace the pipeline with minimum disruption to production, and ensuring against leakage in the meantime through monitoring of the worst locations identified in this assessment. This risk-based remnant life assessment has therefore been key to providing the information necessary to help the shareholders form a decision by consensus within such a difficult problem.

8.5 Conclusions

The problem addressed in this case study was very complex, mainly due to the political and extremely contentious nature of the situation. A small number of very powerful stakeholders were involved in and affected by the decision. Therefore, all voices wanted to be heard. The problem was also complicated by the significant uncertainties in the integrity and remnant life assessments and the consequences of pipeline failure.

The stakeholders were therefore, a significant issue to be addressed in the decision-making. To address this problem the areas of conflict and the areas of agreement were identified. The areas of conflict were put to one side as secondary issues (e.g. which budget to use to pay for any remedial work). This meant that focus could be placed on the areas of agreement (e.g. safeguarding the revenue stream, limiting the risk of pollution, etc.). This is a simple and logical way of building consensus.

The alternatives were identified by discussion with the stakeholders. The minority shareholders, who were keen for the remedial work to be funded from the OPEX budget, proposed a number of repair options. However, the majority stakeholders, who were keen for the remedial work to be funded from the CAPEX budget, proposed options for replacement. Due to the conflicting views in the decision, the two sides of the argument were therefore well represented in the alternatives that were proposed.

The criteria on which the decision was based were identified by discussion amongst the stakeholder group. As discussed above the two main stakeholder groups agreed on the integrity of the pipeline being the most important criterion, in terms of both maximising the revenue stream and minimising the risk of pollution. The other decision criteria which could not be agreed upon were the cost of remedial work, the budget that would pay for remedial work and the timing of remedial work. However, these secondary issues faded into unimportance following the results of the risk assessment, which showed that immediate and significant remedial action had to be taken.

Structural analysis was not used to help understand the problem in this case as the stakeholders simplified the problem through tight constraints on the decision,. For example, as the company had a no leak policy, failure and therefore consequence of failure did not need to be considered in any detail. This meant that once failure of the pipeline had been discovered to be almost a certainty in the near future, the decision problem became a one of repairing or replacing the pipeline as soon as possible.

The information required for the risk assessment was readily available from the company, due to the large number of inspections that had been carried out over the years. The company had been disciplined in maintaining records and therefore the information was straightforward to obtain. There were of course uncertainties in the data and more data would have reduced these uncertainties, however the risk analysis was designed to consider these uncertainties.

The most significant risk, therefore that had to be accounted for was the probability of failure. This was dependent on uncertainties in the historic and future corrosion rate in the pipeline, the current condition of the pipeline and the operating conditions of the

pipeline. The risk assessment model that was developed within this case study was designed to consider these uncertainties in the assessment of the probability of failure of the pipeline over time. The level of engineering detail involved in the risk assessment was considered necessary to model the uncertainties as effectively as possible and to provide a robust prediction of the remnant life of the pipeline. This prediction had to withstand detailed scrutiny from both groups of stakeholders. The fact that the risk assessment had been carried out by an independent third party gave credibility to the results and re-assured the stakeholders that no bias had been included. Sensitivity analysis had also been carried out to determine the influence of some of the main assumptions on the results. This also gave credibility and reassurance to the stakeholders. Once the results of the risk assessment had passed this scrutiny, they became the main basis of the decision.

The risk assessment therefore, succeeded in simplifying the issues by focussing attention on the severity of the problem. This made the decision quite clear. The number of locations along the pipeline with an unacceptable risk of failure both now and in the future meant that repair of the pipeline was not economically viable. This therefore forced the decision to a consensus on replacement. The presence of the third party risk analyst as a facilitator in the shareholder meeting, in which the final decision was made, gave further credibility and confidence to the decision.

The purpose of the risk assessment therefore, was to clarify the issue and to force agreement from all stakeholders. The severity of the problem meant that the previously identified preferences held by the stakeholders became irrelevant, and the overwhelming agreement between stakeholder groups of not allowing leaks dominated the decision. The option of replacing the pipeline became the only effective way of achieving this objective.

The clarity and overwhelming logic of the final recommendation meant that this was fully taken on board by all the stakeholders. The stakeholders gained confidence and reassurance in the decision from the detailed risk analysis and the structured manner in which the results were used.

In this case study, the use of the risk-based decision model did not significantly influence the role of the risk analysis in the final decision. This was due to the significance of the risk and the consensus by the stakeholders to minimise the risk. In fact, the risk analysis dominated the decision above all other issues in the decision process. The expected problems with stakeholder issues were resolved as a result of the risk analysis and the selection of alternatives and decision criteria were governed by the risk assessment results. The use of the risk-based decision model did therefore, help the decision-makers gain a clearer understanding of how to integrate the results of the risk analysis into the decision-making.

The decision problem addressed in this case was very heavily biased to risk assessment rather than any other aspect of decision-making. Even the stakeholder issues that were expected to cause a problem paled into insignificance in the light of the risk assessment results. However, the risk-based decision model was still found useful to ensure that all

aspects of the decision were considered and evaluated. It also provided opportunities for the more detailed risk analyses to be carried out and integrated into the decision.

The application of the risk-based decision model to this case study ensured that all aspects of the situation were considered. Including enforced assurances that the stakeholder issues had been resolved. The use of the decision model also helped identify the role of the risk analysis in the decision. Furthermore, it clarified how the results of the analysis could be used and presented to the stakeholders.

The use of a structured decision process to support the decision in this case helped the decision-makers identify the most important issues to be addressed and the issues, which did not need to be addressed. It allowed the role of the risk analysis in the decision-making to be clearly defined and the detail of analysis to be agreed upon. The use of the risk-based decision model brought the significance of the risks to the fore and meant that the assessment of risks was an integral part of the decision process. The clear structure of the decision process promoted understanding and ownership of the way the decision was made, which gave support for the results that were implemented. Furthermore, it provided the decision-makers with an audit trail to show the logic and thoroughness of the decision-making in case anything went wrong at a later stage.

9 CASE STUDY 4

PRIORITISATION OF BRIDGE STRENGTHENING WORKS

9.1 Problem Definition

9.1.1 Identify problem or opportunity

Due to the very tight limits on budgets, a consortium of bridge engineers from every borough in London, was faced with the difficult problem of selecting the most important bridges for strengthening and repair. Only a small selection of those bridges requiring repair and strengthening could be put forward for funding from the next year's budgets. The decision that had to be made was: "which bridge or bridges out of all those which had been assessed to 40 tonne loading but had failed, should be selected for funding to be brought up to 40 tonne capacity within the next year?"

The client requested that decision should be simplified to consider the present year only, in isolation of any future year's decision. Any bridges that were selected for strengthening this year would not need to be submitted in the following year. Each year the list of bridges requiring strengthening would be updated to include the effects of deterioration. In other words, bridges left over from the previous year may have an increasingly deteriorated condition and additional bridges may have to be added to the list that have deteriorated to an insufficient capacity over the previous year. A more rigorous approach would have been to model the deterioration of the bridges stochastically and make a prediction of the future capacity of the bridge depending on different actions. It was felt that although this meant long term planning was not possible it terms of predicting the condition of the bridges in future years, neither was the prediction of future budgets possible. As there were so many uncertainties to account for, it was decided that a simple method of information gathering and bridge selection every year would be preferable to a detailed time dependent analysis of each bridge with a once off long-term strengthening and maintenance plan. This meant that the annual process of selection between alternatives would be more manageable.

The problem of prioritising bridges for strengthening involves quantitative assessments of factors such as capacity of the bridge, traffic disruption and strengthening costs as well as subjective judgements of other less well defined issues such as impacts on the local community of traffic restrictions on the bridge. When such multiple criteria are used, certain "trade-offs" are required, as different bridges would score better in terms of different criteria considered in isolation.

9.1.2 Identify stakeholders in the decision

Due to the importance of London in terms of industry, commerce, tourism and politics a wide range of stakeholders had to be taken into account in the decision-making process. The decision, after all, had to be seen to be the best for London as a whole since the funding was supplied for London as a whole. Each borough of London represents very different cultures, different focuses and different economies; therefore, the views and perceptions of each of the stakeholders were very diverse.

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. One of the first stages in preparing for the decision analysis, therefore, was to determine who was in the decision-making group and to what extent each person could and wanted to, influence the decision.

9.1.2.1 The external stakeholders

Discussions with borough council representatives indicated that the external stakeholders would include users of the bridge (private, commercial and industrial), environmental pressure groups (campaigning for improved facilities for environmental transport such as bus lanes, cycle lanes, etc.) and government officials (Local Councillors, MPs from local constituencies, etc.). In each of the boroughs, these groups of stakeholders would have different profiles, dynamics and powers. For example, in North West London, the local economies rely heavily on light industry and transportation (e.g. for supplying Heathrow airport). In South West London, the economies are driven by a combination of commerce and tourism. This means that very different priorities exist in the two areas.

9.1.2.2 The internal stakeholders

There are two main groups of internal stakeholders, the asset managers and the asset management group.

The asset manager is the chief borough bridge engineer in each of the London boroughs who is responsible for the safety and maintenance of all bridges in that borough. This involves planning and allocating budgets to inspection, routine maintenance, repair, strengthening and upgrading of all bridges in the borough.

The asset management group is the committee responsible for allocating annual budgets for each asset manager. In this decision problem, this was the London Bridge Engineering Group itself. This group consisted of four borough bridge engineers each elected to represent the group of London boroughs in each of the four quadrants of London, a separately elected chairman (also a borough bridge engineer) and a representative of the Governors of London who control the overall budget. Early on in the project it was necessary to identify what the dynamics of this group were, who held the power in the group, and how decisions were made and agreed within the group.

In order account for all stakeholder views in the decision process, it would have been ideal to interview a number of borough bridge engineers and a number of representatives from other stakeholder groups. These would include representatives of the local chamber of commerce, the council representatives for public transport, figures from local industry, local members of parliament and representatives for environmental pressure groups. However, again due to restrictions on time, representatives of four borough councils were interviewed, these included borough bridge engineers and council representatives of constituency needs.

9.1.3 Identify viable alternatives

The alternatives in this decision were the many bridges that required strengthening. However, there was the possibility that more than one bridge could be selected to ensure best use of the allocated budgets, therefore the number of alternatives was far more than the number of bridges requiring repair as a large number of combinations of bridges could also be selected.

The client had already dictated that each bridge submitted for funding should propose a fully costed repair schedule. Therefore, by the time the bridges were considered for prioritisation, the repair/strengthening option had already been defined. This therefore could not be considered as part of the decision alternatives. A more rigorous approach would have been to formally determine the best repair/strengthening strategy for each bridge then to determine which bridges to strengthen in the next financial year. This however would have been extremely complex (as more than 150 bridges were under consideration) and time consuming.

Each borough bridge engineer was asked to provide a list of bridges in their boroughs requiring strengthening work and they were given a questionnaire to complete for each bridge to evaluate each bridge against the given criteria. These criteria are discussed below.

9.1.4 Formulate decision objectives and criteria

The final part of defining the decision problem was identifying the criteria on which the decision was to be based. The decision criteria were identified very early on in the analysis by interviewing experienced bridge engineers and other council representatives who were representing the views of external stakeholders (such as local business and industry). In addition, previous work for the Scottish Office [108] was reviewed as were other prioritisation systems already in existence, such as those at Hertfordshire and Essex Councils.

A comprehensive list of factors was produced and this was then refined and condensed through discussions with a number of boroughs. However, some of these criteria (such as social impacts) were not straightforward to measure. Therefore hierarchies of criteria were developed that would enable the top-level criteria to be evaluated. Again, this was carried out in discussion with the area representatives. For each top-level criterion, a brainstorming session identified all the factors that were needed to be able to calculate a value for the parent criteria. All of these sub-criteria were then discussed in detail. Some sub-criteria were discarded if it was felt that they were duplicated elsewhere. Other sub-criteria were identified as contributing to another sub-criterion, so these were demoted to a lower lever in the hierarchy. This process of discussion and evaluation continued until it was felt that the families of criteria were independent, complete and measurable. The proposed hierarchies of criteria are defined below. The Analytic Hierarchy process [100] was used to help 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. This can work towards being able to score each of the bridges

against the identified criteria, since it was not possible to directly measure each bridge for some of the criteria. The main criteria on which the bridge prioritisation decision was to be based were found to be:

- The cost of carrying out strengthening work
- The risk of bridge failure if strengthening work is not carried out
- The cost of interim measures such weight restrictions, or propping if strengthening work is not carried out immediately,
- The impacts on the local society if the work is not carried out
- The additional benefits that can be gained by carrying out bridge improvement and upgrading works at the same time.

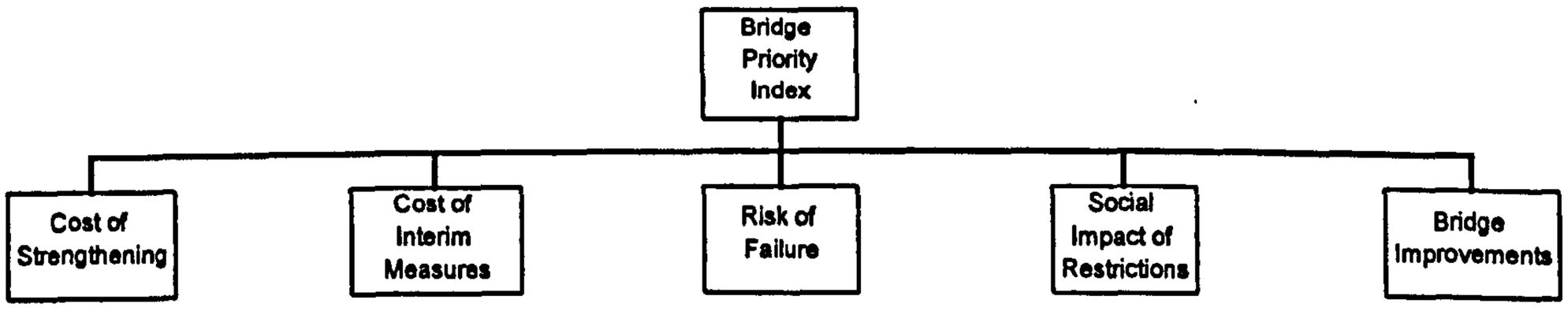


Figure 21: The proposed main criteria for deriving bridge strengthening priorities

These criteria are defined with their sub-criteria in more detail below:

9.1.4.1 Cost of strengthening works

Since the main issue in prioritising the bridges is the optimal allocation of resources from the annual budget, the cost of carrying out the strengthening work on each bridge should be taken into account.

The factors that were identified to evaluate the cost of strengthening works are shown in Figure 22. These are the cost of carrying out the work (labour, material, equipment), as stated in the works budget, the cost of traffic management schemes (lighting, signing, cones, etc.), and the cost of traffic delays (imaginary cost), during the works.

The cost of works was taken directly from the estimate for the strengthening work made by the assessing engineer. The cost of implementing the necessary traffic management schemes during the strengthening work was also provided by the assessing engineer's estimates. The costs associated with the traffic disruption caused by the strengthening works was taken from look-up tables for costs of diversion and delays based on the assessing engineer's estimate of the likely traffic flows, the make up of those flows, diversion lengths, road types, etc.

Since all of these factors are measured in terms of cost, they can be aggregated directly into an overall cost to represent the cost of strengthening for the particular strengthening project under consideration.

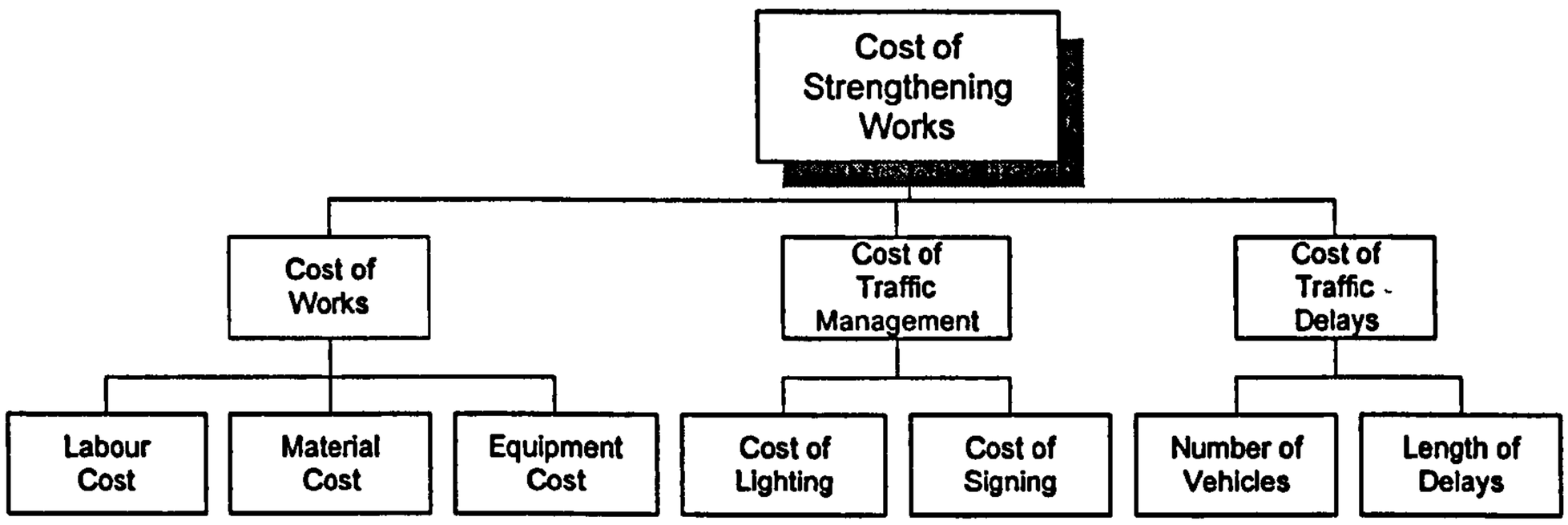


Figure 22: The proposed sub criteria for deriving the cost of carrying out strengthening works

9.1.4.2 Cost of interim measures

The prioritisation system was intended to consider only bridges that have failed the structural assessment, so until the strengthening work was completed, it may have been necessary to implement certain interim measures. These could include weight restrictions, lane restrictions, propping, etc. The costs of implementing such interim measures would be saved if strengthening work was carried out.

The costs associated with implementing interim measures included costs associated with traffic disruption (real and imaginary costs due to delays and diversions) incurred by the implementation of weight or lane restrictions on and around the bridge. In addition, the costs of implementing and maintaining interim measures such as road signs and markings to indicate weight or lane restrictions or the cost of strengthening work (e.g. propping, etc.) was also considered. Figure 23 below shows the hierarchy of these costs.

The costs associated with the traffic disruption caused by the implementation of interim measures were taken from look-up tables for costs of diversion and cost of delays based on the assessing engineer's estimate of the likely traffic flows, the make up of those flows, diversion lengths, road types, etc. The cost of implementing and maintaining the interim measures was taken directly from estimates made by the assessing engineer.

Since all of these factors are measured in terms of cost, they can be aggregated directly into an overall cost to represent the cost of interim measures for the particular strengthening project under consideration.

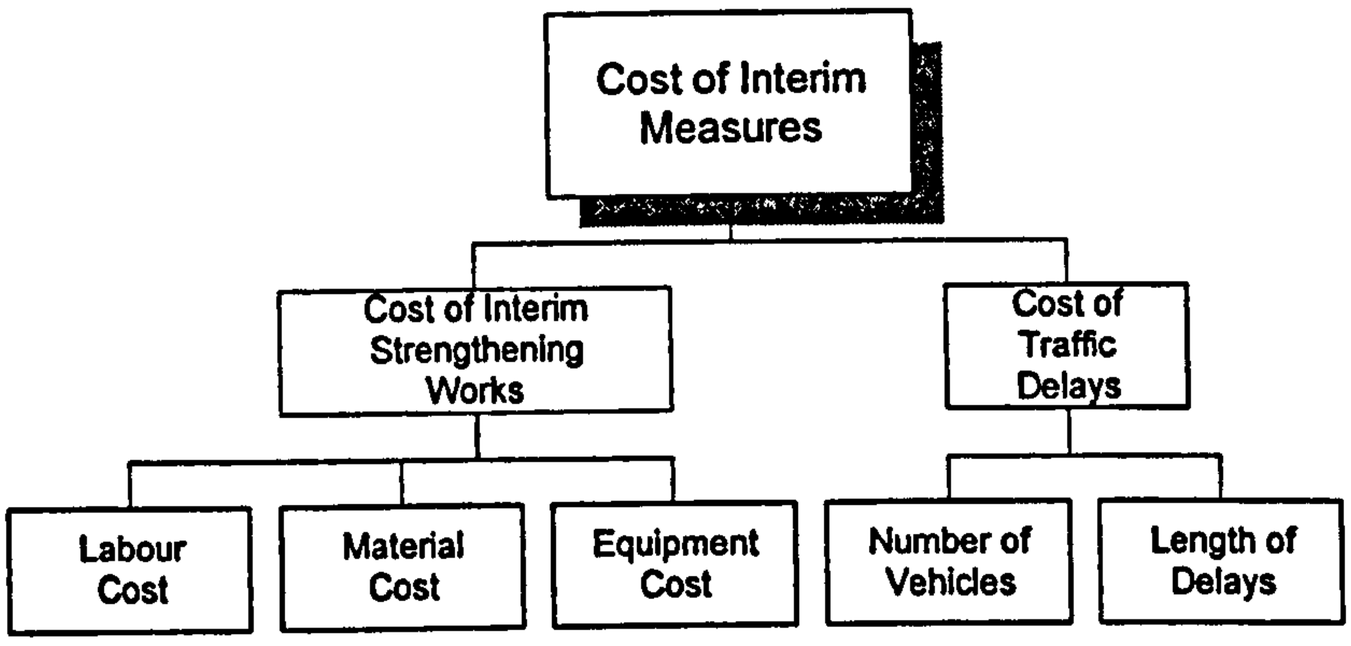


Figure 23: The proposed sub criteria for deriving the cost of carrying out interim strengthening works

9.1.4.3 Risk of bridge failure

Despite a bridge failing an assessment, it is not feasible in all cases to implement interim measures, such as weight restrictions, to maintain safety. In these cases, the risk of bridge failure can be high. In other situations, the risk of the bridge failing under standard operation is considered acceptable. Calculating the probability of the bridge failing under standard operation and assessing the failure consequences provides a comparison with the cost of interim measures. This is because a bridge without interim measures will have both a higher probability of failure and higher consequences of failure (e.g. more traffic would continue to use the bridge subjecting more people to the risk). This therefore should be taken into account in establishing bridge priorities. Obviously, this risk will be greatly reduced if the strengthening works are carried out.

The risk of bridge failure was evaluated as a function of the probability of failure and its consequences. The consequences of failure included the costs of emergency repairs, the cost of traffic disruption caused by the closure of the bridge, costs associated with any fatalities, injuries, and the environmental damage that may have occurred because of bridge collapse. These factors are shown in Figure 24. The probability of failure was calculated as a risk index based on the assessed capacity of the structure based on Reference [108]. This is described in more detail in Section 9.3.

The probability of failure was evaluated by defining a base probability of failure from the current restricted capacity ratio based on a look up chart. Modifying factors were then applied to account for the road type, effect of impact, span length, live load, any reserve strength and redundancy considered by the assessing engineer and any proposed inspection regime. These factors were all determined by using look-up charts based on the data provided by the assessing engineer.

The consequences of failure were evaluated by combining the following costs:

- The costs associated with the traffic disruption caused by the failure of the bridge. These were taken from look-up tables for costs of diversion and cost of delays based on the assessing engineer's estimate of the likely traffic flows, the make up of those flows, diversion lengths, road types, etc.

- The cost of emergency repairs to the bridge following collapse. This was taken directly from the assessing engineer's estimate.
- The cost of human fatalities and injuries. This was determined from a look-up table based on data supplied by the assessing engineer on traffic flow, span length, number of lanes, the type of failure and the warning expected of any failure.

The final combination of probability of failure and cost consequences of failure resulted in an overall cost assessment of risk for the particular bridge-strengthening project under consideration.

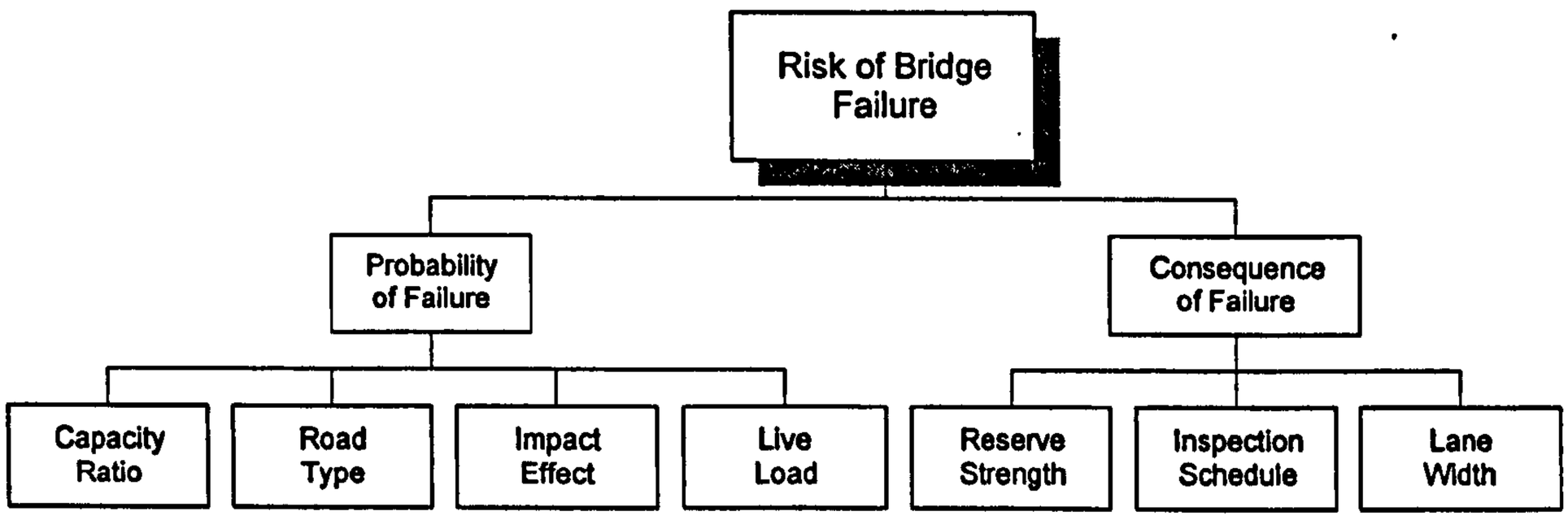


Figure 24: The proposed sub criteria for deriving the risk of bridge failure

9.1.4.4 Social impact of restrictions

The less tangible factors that needed to be considered in establishing bridge priorities were grouped together under the heading "social impact" of the route. This covered all of the non-costed impacts on the local community of the traffic restrictions on the bridge such as, the inconvenience of bus routes being diverted away from their usual stops and the discomfort of HGVs being diverted through residential areas. The inconvenience of a closed bridge to cyclists and pedestrians who will take much longer to take another route was also accounted for. These impacts depended on the type of traffic and the daily traffic flow on the route, the type of route and the availability of alternative routes and would not occur if the strengthening works were carried out.

The sub-criteria on which the impact on society was to be based were, therefore, divided into two groups: the category of the route and the importance of the route. The category of the route was evaluated from the daily traffic flow on the route and the type of route (i.e. Primary Route, Borough Principal Route, etc.). The importance of the route was based on the type and numbers of vehicles using the route and the availability of alternative routes for each type of vehicle. This hierarchy is shown in Figure 25 below.

The category of the route was evaluated from the data supplied by the assessing engineer for the daily traffic flow on the route and the type of route (i.e. primary route, Borough Principal Route, etc.) An importance weight was applied to each type of route by asking each expert to make comparisons between each pair of route types in a similar

way to that presented in Section 9.4. The appropriate weight will then be multiplied by the daily traffic flow to give a score for the route category.

The importance of the route will be evaluated by firstly identifying the importance of the route for each type of user. This will be done by identifying the code for the amount of use by that category of user, from the flow code and the possible alternative routs available for that category of user. These are available from the data provided by the assessing engineer. To calculate a score for the possible alternative routes, the experts will be asked to make comparisons between each pair of alternative route types in terms of inconvenience and discomfort to the community, in the manner presented in Section 9.4. The appropriate score was then determined by mapping the alternative route code onto the consensus set of scores. A similar method was applied to determine scores for each of the flow codes for each of the different types of users. The scores for the type of alternative route and the flow for each type of user were combined to give a score for the importance of the route for each type of user.

Again, the experts were asked to compare the importance of each type of user in terms of the inconvenience and discomfort to society so that each score could be aggregated in terms of its importance to obtain an overall score for the route importance. Weights were then determined from interviews with the experts, to rank the route category against the route importance to evaluate a score overall for the social impact of the route.

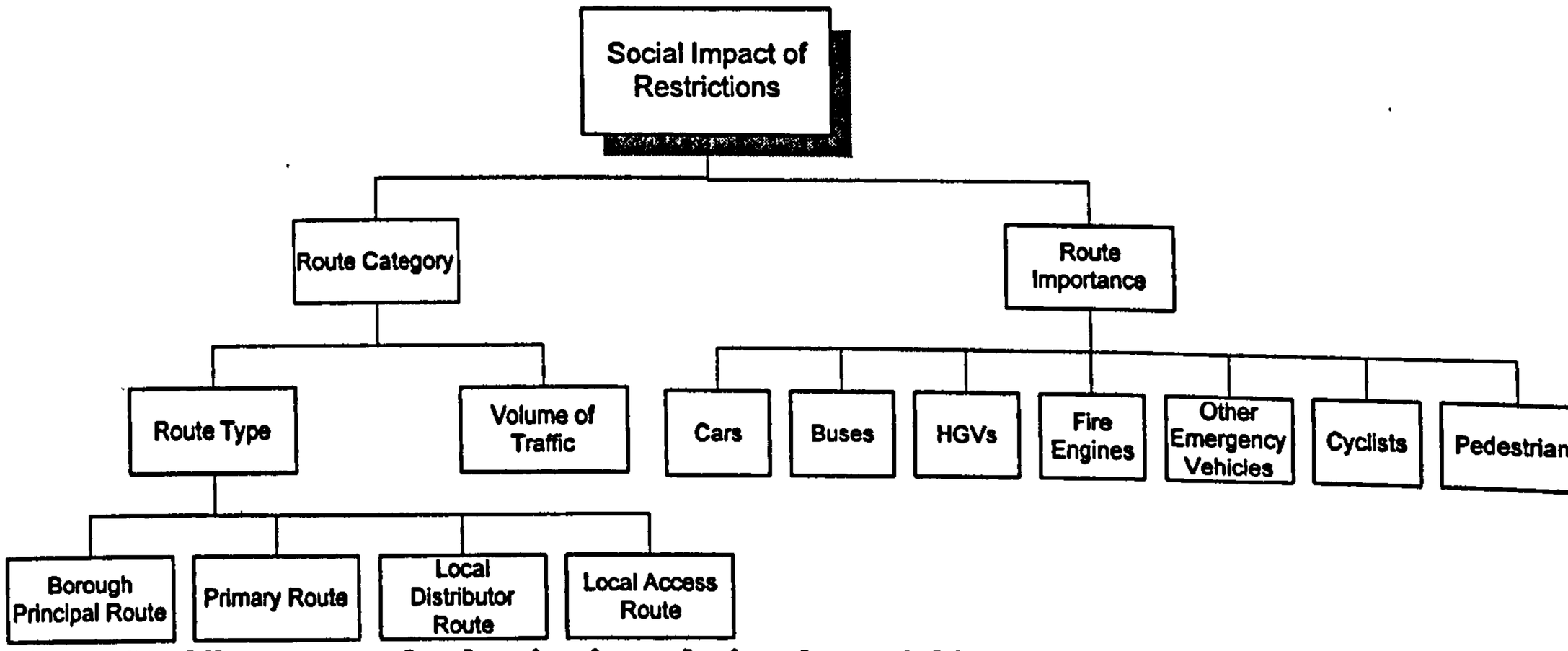


Figure 25: The proposed sub criteria to derive the social impact of the restrictions

9.1.4.5 Bridge improvement benefits

When strengthening works are carried out on a bridge, work is also often carried out to remove some substandard features identified under the Upgrade and Improvement clause of the 15-year Rehabilitation Programme. If these upgrading works are carried out in parallel with the strengthening work, funded by a separate budget, not only is the functionality and safety of the bridge further improved but also savings are made in traffic management cost, etc., from combining the works.

The benefits of bridge improvement works depend on the types of bridge improvement works that are carried out. These were identified are from a list of all the proposed upgrading works specified in the data form by the assessing engineer. The types of works considered were strengthening for HB vehicles, carriageway widening, footway widening, provision of additional services, and improvement of sight distance and strengthening of the parapets. In addition, any improvements that fulfil the London wide strategy for cycle lanes, bus lanes, etc. are also considered. These are shown in Figure 26.

At this stage, all that was required from the assessing engineer was a yes/no statement of whether each type of upgrading work was proposed. For this reason, all types that were proposed were scored 1 and all types that were not proposed were scored 0. Weightings were obtained, again by interviewing the experts, to identify the relative importance of each type of upgrading work. The score for the work was then multiplied by its weight and all of these were summed to give an overall score for bridge improvement.

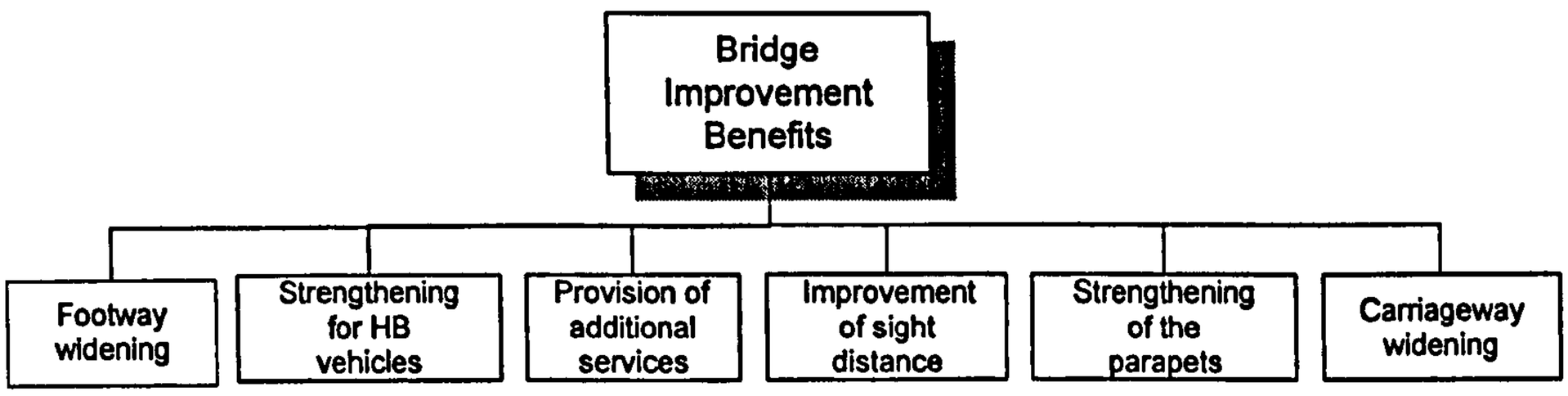


Figure 26: The proposed sub criteria for deriving additional benefits due to bridge improvements

9.2 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. In these situations, the structuring process 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. Either a decision tree or an influence diagram can represent these. An influence diagram, provides a simple 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 [24]. 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 become confusing and out of hand, [99]. Whichever method of representation is selected does not affect the ultimate decision, as either structure can be converted to the other. Figure 27 shows the influence diagram representing this decision problem.

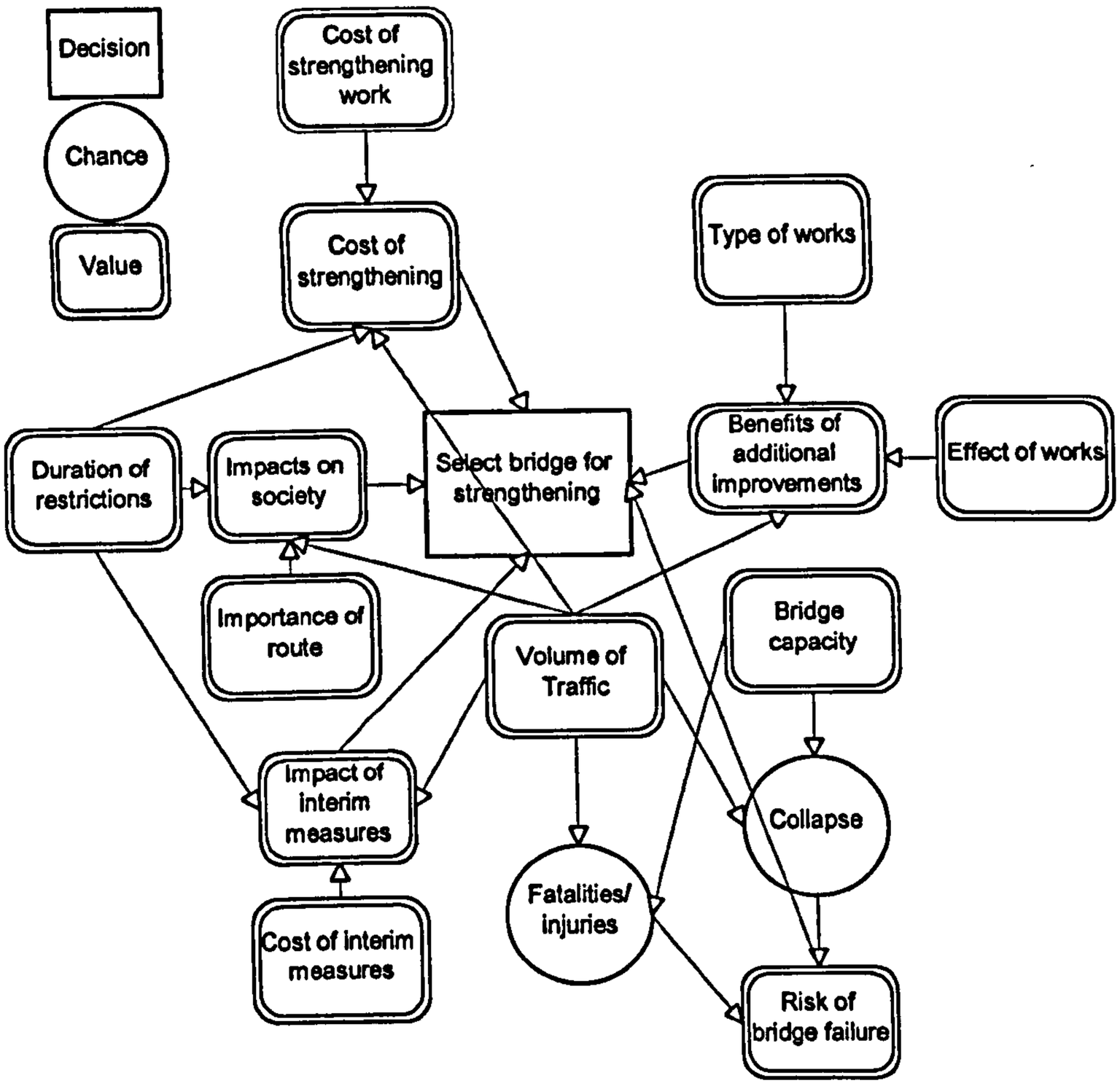


Figure 27: Influence Diagram representing decision problem

9.3 Uncertainty and Probabilistic Analysis

The probability of bridge failure is influenced by uncertainties in the determination of the extreme traffic loads, the inherent randomness of the material properties and uncertainties in the analysis methods used for determining load effects and capacities. Modern structural reliability methods [104] are now widely accepted as a rational method of accounting for uncertainties in these parameters. Although such advanced reliability and risk analysis methods are available for evaluating the risk of a bridge failure (see case study 2), they are generally not suitable for use on a routine basis. This is due to their complexity and the general lack of expertise in risk analysis among bridge assessment engineers. This is especially pertinent when considering a wide range of bridge types as those represented in the London area.

The client therefore requested that only a simplified approach to risk quantification be adopted again due to pressures of time and availability of information. A more rigorous approach would have been to develop probabilistic loading and strength models for each bridge under consideration. The probability scoring system adopted is similar to that presented in [108].

The aim of the probability scoring system was to enable reliability assessment to be carried out quickly and simply for all bridge types. This enabled the probability

information concerning bridge failure to be used more rationally in the decision-making process.

The probability score was calculated by first defining a base level score as a function of the capacity ratio. This was then modified by factors that account for bridge specific features as presented below:

1. Road type: Based on the class of the road over the bridge and the number of vehicles using it per day.
2. Impact effect: Based on the dynamic characteristics of the bridge and the vehicles using it, and on the surface roughness and pavement condition.
3. Reserve strength: Based on the ratio of the ultimate capacity of the bridge and the capacity of the component considered.
4. Inspection schedule: Based on the level of inspection to which the component is subjected and the amount of warning of failure expected to be given.
5. Live load: Based on the significance of the live load compared to the total load to which the bridge is subjected.
6. Lane width: Based on the amount of traffic than can be carried over the bridge in contra-flow situations.

9.4 Utility/Value Analysis

It was considered very likely that bridge managers would consider one criterion more important than the other. The bridge manager was also very likely to have some idea of the relative importance that should be given to each of the main factors in considering the various bridge strengthening projects. For example, the risk of the bridge collapsing was probably going to be considered more important than the cost savings that can be gained from combining the strengthening project with upgrading work. However, the problem was how to quantify the weighting that should be given to each criterion. Obviously, this was a judgmental issue, and the best approach was felt to ask the decision-makers. However, deriving the relative weights for each criterion meant that the "trade-off" issues had to be accounted for arising from the multiple criteria nature of the decision problem. It was necessary for the relative weights to reflect the preferences of the decision-makers (bridge managers) for each criterion in relation to the other criteria. However, it can be very difficult to directly assign such weights to each factor in a rational manner. More consistent responses can be obtained when opinions are sought about the relative importance of pairs of criteria. This is because the human mind finds it very difficult to visualise more than two or three criteria/situations at one time. In this study therefore, bridge managers were interviewed to obtain the relative importance they attached to pairs of criteria according to the Analytic Hierarchy process. This would be formally carried out as in the following example:

To compare two factors such as the risk of failure and the cost of strengthening, the decision maker would be asked to state, which is considered more important. If there was no preference then the next comparison would be made. If, however, the decision-

maker had a preference between the factors this would be indicated on the following scale:

1	Equally preferred
3	Weak preference
5	Strong preference
7	Very strong preference
9	Absolute preference

Intermediate values of 2, 4, 6, 8 may also be used

It was felt that asking each bridge manager to make his or her comparisons directly on the scale specified by Saaty would be difficult and time consuming. In addition, the use of a subjective non-dimensional scale such as Saaty's was likely to result in inconsistent evaluations between interviewees. One person's strong preference could be another's very strong preference. Engineers, also tend to have a natural aversion to non-dimensional scoring systems, they like to know the meaning and the effect of the numbers. This natural discomfort with such methods results in the bridge managers becoming impatient, agitated and disillusioned. Therefore, I developed an extension to this method to support the comparisons.

9.4.1 Definition of criteria ranges

First each criteria was banded such that, for example "high risk of failure" was quantified. This was based on expert opinion and was carried out with this specific bridge selection problem in mind. Table 31 - Table 35 present the definition of each criterion bands.

Cost of Strengthening Works	v. low	low	med.	high	v. high
Cost of work	£100k	£200k	£500k	£800k	£1m
Cost of traffic delays	£900k	£4m	£45m	£180m	£380m

Table 31 Definition of criteria ranges for "cost of strengthening works"

Cost of interim measures	v. low	low	med.	high	v. high
Daily	< £5k	£25k	£250k	£1m	£2m
Annual cost	< £1.8m	£9m	£90m	£350m	£750m

Table 32 Definition of criteria ranges for "cost of interim measures"

Risk of bridge failure	v. low	low	med.	high	v. high
Capacity ratio	0.95	0.9	0.8	0.7	0.6
Chance of failure	1 in 10^6	1 in 10^5	1 in 10^4	1 in 10^3	1 in 100
No of fatalities	0	0	1	5	15
Cost of traffic delays	£500k	£5m	£50m	£100m	£300m

Table 33 Definition of criteria ranges for "risk of bridge failure"

Social impact of restrictions	**v. low**	**low**	**med.**	**high**	**v. high**
Type of road	Local access road	Local distributor road	Primary/ Borough principal road	Primary/ Borough principal road	Primary/ Borough principal road
No of vehicles per day	5000	12000	15000	20000	30000
No of buses & trucks per day	500	1000	2000	3000	4000
Importance for fire engines & other emergency vehicles	access only	access only	important route	very important route	very important route

Table 34 Definition of criteria ranges for "social impact of restrictions"

Bridge improvement benefits	**low**	**med.**	**high**
Type of bridge improvement works	Strengthen for HB vehicles Widen carriageway	Strengthen parapets Increase sight distance	Widen footway Provide additional services

Table 35 Definition of criteria ranges for "bridge improvement benefits"

If there had been more time and interest from the final users, then Fuzzy logic could have been used to quantify these bands, making the boundaries between the bands more flexible.

9.4.2 Definition of scenarios

Once these bands had been defined, a series of decision scenarios were defined that considered one pair of criteria at a time. These scenarios were defined as if there were two almost identical bridges that only differed with respect to the two criteria currently under consideration. For example, for the pair wise comparison of the criterion "social impact of restrictions" with the criterion "cost of strengthening works", the decision maker would first be asked which out of two almost identical bridges, A and B, would he choose to fund for strengthening. Initially bridge A was defined as having a very high cost of strengthening but a very low social impact if restricted, and bridge B had a very high social impact if restricted but a very low cost of strengthening. The definitions of very low, low, medium, high, and very high, as shown previously, were displayed for each criteria at all times. It is obvious at this stage that if all else were equal, bridge B would be strengthened first. The scenario would then be changed such that the bridge selected previously (i.e. Bridge B) would have a reduced first criterion and an increased second criterion.

The bridge not selected would stay the same. In other words, the second comparison would be between bridge A still with a very high cost of strengthening and a very low social impact if restricted, and bridge B now with a high social impact if restricted and a low cost of strengthening. Again, the decision-maker would be asked to choose a bridge for strengthening. These scenarios would continue along the scales, until the

decision-maker reached a crossover point where, the initially preferred bridge ceased to be preferred.

All of the choices were marked on a response sheet (as shown in Appendix 5) and this crossover point then implied a degree of preference between criteria. This process was repeated for all pairs of criteria until a full pair-wise comparison matrix could be completed.

This process was repeated for each group interviewed to ensure that a full representation of each individual's views was obtained. Four different interviews were carried out in total with different groups of decision-makers. Group 1 involved a borough bridge engineer, a traffic planner and a council representative. In this group, the whole interview took nearly three hours, as there was significant disagreement between the three representatives. The borough bridge engineer was most concerned with safety, the traffic planner was most concerned with traffic disruption and the council representative was most concerned with the impacts on society and local businesses. Because of these differences in personal priorities, it took quite a while, in some comparisons, for the three to reach a consensus. Group 2 consisted of one borough bridge engineer alone. In this case, the interview took almost as long as the Group 1 interview, but for different reasons. In this interview, the bridge engineer had no one to bounce his ideas off and therefore it took a while for him to come to a conclusion in some questions. The last two groups consisted of two engineers each, Group 3 was a borough bridge engineer and a traffic planner, and group 4 was a borough bridge engineer and a council representative. Both of these groups found the questions much easier to answer as they consisted of people with similar priorities.

9.4.3 Processing of results

The results of this questionnaire were processed to determine relative weights for each "family" of criteria. The relative weights were evaluated by constructing a conversion scale from the interview results to Saaty's 1 to 9 scale. This scale is shown in Table 36.

This scale was then applied in the following manner. The decision maker could state, for example, that Bridge A with very high risk and very low cost of strengthening was of the same priority for strengthening as Bridge B with very low risk and very high cost of strengthening. This would mean that the two criteria must be of equal importance. This means this comparison would score a "1" on Saaty's scale. Alternatively, the decision maker could give Bridge A the priority until it had a low risk of failure and very low cost of strengthening and Bridge B remaining constant. This comparison would then score a 7. If the crossover occurred between two comparisons then that would give an intermediate score.

Saaty's Scale	1	2	3	4	5	6	7	8	9
Dominant Bridge Criterion 1	very high		high		med.		low		very low
Dominant Bridge Criterion 2	very low		very low		very low		very low		very low
Secondary Bridge Criterion 1	very low		very low		very low		very low		very low
Secondary Bridge Criterion 2	very high		very high		very high		very high		very high

Table 36 Scheme used to interpret interview responses

A set of pair-wise comparison matrices was constructed for each family of criteria :

1. The top level family of criteria i.e.:
   - Risk of failure, Cost of strengthening works, etc.
2. Three families of criteria for the evaluation of the social impact of restrictions i.e.:
   - Route importance versus Route category
   - Primary Route, Borough Principal Route, etc.
   - Fire Engines, Emergency Vehicles, etc.
3. One family of criteria to determine the benefit of bridge improvement works i.e.:
   - High benefit (strengthen to 40t), medium benefit (increase sight distance), etc.

Two sets of results were generated, the first was created from the interviews at the time of the project; the second (shown in parentheses) was generated more than a year later from the same interview documentation. This was to see how much my own interpretation of the results differed between the two independent occasions, and how that affected the outcome. These are shown in the following set of tables.

9.4.3.1 Top level family of criteria

Group 1 Results	Cost of Strengthenin Works	Cost of interim measures	Risk of bridge failure	Social impact of restrictions	Bridge improvement benefits
Cost of Strengthening Works	1	1/6 (1/6)	*1/9(1/9)*	1/7 (1/7)	1/3 (1/3)
Cost of interim measures	6 (6)	1	1/7 (1/6)	1/5 (1/5)	*5 (6)*
Risk of bridge failure	*9 (9)*	7 (6)	1	6 (6)	*8 (7)*
Social impact of restrictions	7 (7)	5 (5)	1/6 (1/6)	1	6 (5)
Bridge improvement benefits	3 (3)	*1/5 (1/6)*	*1/8 (1/7)*	1/6 (1/5)	1

Table 37 Pair wise comparison matrix for level 1 hierarchy (group 1 results)

Group 2 Results	Cost of Strengthenin Works	Cost of interim measures	Risk of bridge failure	Social impact of restrictions	Bridge improvement benefits
Cost of Strengthening Works	1	1/3 (1/2)	*1/7* (1/5)	1/3 (1/2)	2 (2)
Cost of interim measures	3 (2)	1	1/6 (1/4)	1/4 (1/3)	*3* (*3*)
Risk of bridge failure	*7* (*5*)	6 (4)	1	4 (4)	*8* (*6*)
Social impact of restrictions	3 (2)	4 (3)	1/4 (1/4)	1	4 (4)
Bridge improvement benefits	1/2 (1/2)	*1/3* (*1/3*)	*1/8* (*1/6*)	1/4 (1/4)	1

Table 38 Pair wise comparison matrix for level 1 hierarchy (group 2 results)

Group 3 Results	Cost of Strengthenin Works	Cost of interim measures	Risk of bridge failure	Social impact of restrictions	Bridge improvement benefits
Cost of Strengthening Works	1	1/5 (1/6)	*1/8* (1/8)	1/7 (1/7)	9 (6)
Cost of interim measures	5 (6)	1	1/7 (1/7)	1/6 (1/8)	*9 (7)*
Risk of bridge failure	*8 (8)*	7 (7)	1	6 (6)	*9 (9)*
Social impact of restrictions	7 (7)	6 (8)	1/6 (1/6)	1	9 (8)
Bridge improvement benefits	1/9 (1/6)	*1/9 (1/7)*	*1/9 (1/9)*	1/9 (1/8)	1

Table 39 Pair wise comparison matrix for level 1 hierarchy (group 3 results)

Group 4 Results	Cost of Strengthenin Works	Cost of interim measures	Risk of bridge failure	Social impact of restrictions	Bridge improvement benefits
Cost of Strengthening Works	1	1/5 (1/6)	*1/9 (1/8)*	1/7 (1/7)	4 (5)
Cost of interim measures	5 (6)	1	1/8 (1/8)	1/4 (1/5)	*6 (7)*
Risk of bridge failure	*9 (8)*	8 (8)	1	7 (7)	*9 (9)*
Social impact of restrictions	7 (7)	4 (5)	1/7 (1/7)	1	8 (8)
Bridge improvement benefits	1/4 (1/5)	*1/6 (1/7)*	*1/9 (1/9)*	1/8 (1/8)	1

Table 40 Pair wise comparison matrix for level 1 hierarchy (group 4 results)

9.4.3.2 First family of criteria for evaluating the social impact of restrictions

Group 1 Results	Route Importance	Route Category
Route Importance	1	1/3 (1/4)
Route Category	3 (4)	1

Table 41 Pair wise comparison matrix for level 2 hierarchy (group 1 results)

Group 2 Results	Route Importance	Route Category
Route Importance	1	5 (6)
Route Category	1/5 (1/6)	1

Table 42 Pair wise comparison matrix for level 2 hierarchy (group 2 results)

Group 3 Results	Route Importance	Route Category
Route Importance	1	1/6 (1/6)
Route Category	6 (6)	1

Table 43 Pair wise comparison matrix for level 2 hierarchy (group 3 results)

Group 4 Results	Route Importance	Route Category
Route Importance	1	3 (3)
Route Category	1/3 (1/3)	1

Table 44 Pair wise comparison matrix for level 2 hierarchy (group 4 results)

9.4.3.3 Second family of criteria for evaluating the social impact of restrictions

Group 1 Results	Primary Route	Borough Principal Route	Distributor Route	Local Access Route
Primary Route	1	1	6 (8)	6 (8)
Borough Principal Route	1	1	6 (8)	6 (8)
Distributor Route	1/6 (1/8)	1/6 (1/8)	1	1
Local Access Route	1/6 (1/8)	1/6 (1/8)	1	1

Table 45 Pair wise comparison matrix for 1st level 3 hierarchy (group 1 results)

Group 2 Results	Primary Route	Borough Principal Route	Distributor Route	Local Access Route
Primary Route	1	1	6 (7)	6 (7)
Borough Principal Route	1	1	6 (7)	6 (7)
Distributor Route	1/6 (1/7)	1/6 (1/7)	1	1
Local Access Route	1/6 (1/7)	1/6 (1/7)	1	1

Table 46 Pair wise comparison matrix for 1st level 3 hierarchy (group 2 results)

Group 3 Results	Primary Route	Borough Principal Route	Distributor Route	Local Access Route
Primary Route	1	1	7 (7)	7 (7)
Borough Principal Route	1	1	7 (7)	7 (7)
Distributor Route	1/7 (1/7)	1/7 (1/7)	1	1
Local Access Route	1/7 (1/7)	1/7 (1/7)	1	1

Table 47 Pair wise comparison matrix for 1st level 3 hierarchy (group 3 results)

Group 4 Results	Primary Route	Borough Principal Route	Distributor Route	Local Access Route
Primary Route	1	1	7 (7)	7 (7)
Borough Principal Route	1	1	7 (7)	7 (7)
Distributor Route	1/7 (1/7)	1/7 (1/7)	1	1
Local Access Route	1/7 (1/7)	1/7 (1/7)	1	1

Table 48 Pair wise comparison matrix for 1st level 3 hierarchy (group 4 results)

9.4.3.4 Third family of criteria for evaluating the social impact of restrictions

Group 1 Results	Fire Engines	Emergency Vehicles	Buses	HGVs	Cyclists	Pedestrians
Fire Engines	1	1 (1)	3 (3)	5 (5)	*8 (8)*	*9 (9)*
Emergency Vehicles	1 (1)	1	3 (4)	5 (5)	*8 (8)*	*9 (9)*
Buses	1/3 (1/3)	1/3 (1/4)	1	4 (4)	6 (7)	7 (8)
HGVs	1/5 (1/5)	1/5 (1/5)	1/4 (1/4)	1	5 (6)	6 (7)
Cyclists	*1/8 (1/8)*	*1/8 (18)*	1/6 (1/7)	1/5 (1/6)	1	*2(2)*
Pedestrians	*1/9 (1/9)*	*1/9 (1/9)*	1/7 (1/8)	1/6 (1/7)	*1/2 (1/2)*	1

Table 49 Pair wise comparison matrix for 2nd level 3 hierarchy (group 1 results)

Group 2 Results	Fire Engines	Emergency Vehicles	Buses	HGVs	Cyclists	Pedestrians
Fire Engines	1	1 (1)	5 (5)	7 (6)	*9 (8)*	*9 (9)*
Emergency Vehicles	1 (1)	1	5 (5)	7 (6)	*9 (8)*	*9 (9)*
Buses	1/5 (1/5)	1/5 (1/5)	1	6 (5)	7 (7)	8 (8)
HGVs	1/7 (1/6)	1/7 (1/6)	1/6 (1/5)	1	6 (6)	7 (7)
Cyclists	*1/9 (1/8)*	*1/9 (1/8)*	1/7 (1/7)	1/6 (1/6)	1	*2 (2)*
Pedestrians	*1/9 (1/9)*	*1/9 (1/9)*	1/8 (1/8)	1/7 (1/7)	*1/2 (1/2)*	1

Table 50 Pair wise comparison matrix for 2nd level 3 hierarchy (group 2 results)

Group 3 Results	Fire Engines	Emergency Vehicles	Buses	HGVs	Cyclists	Pedestrians
Fire Engines	1	1 (1)	1/5 (1/6)	1/5 (1/6)	*4 (8)*	*5 (9)*
Emergency Vehicles	1 (1)	1	1/5 (1/6)	1/5 (1/6)	*4 (8)*	*5 (9)*
Buses	5 (6)	5 (6)	1	1 (1)	8 (7)	9 (8)
HGVs	5 (6)	5 (6)	1 (1)	1	8 (7)	9 (8)
Cyclists	*1/4 (1/8)*	*1/4 (1/8)*	1/8 (1/7)	1/8 (1/7)	1	*2 (2)*
Pedestrians	*1/5 (1/9)*	*1/5 (1/9)*	1/9 (1/8)	1/9 (1/8)	*1/2 (1/2)*	1

Table 51 Pair wise comparison matrix for 2nd level 3 hierarchy (group 3 results)

Group 4 Results	Fire Engines	Emergency Vehicles	Buses	HGVs	Cyclists	Pedestrians
Fire Engines	1	1 (1)	8 (7)	5 (6)	*9 (9)*	*9 (9)*
Emergency Vehicles	1 (1)	1	8 (7)	5 (6)	*9 (9)*	*9 (9)*
Buses	1/8 (1/7)	1/8 (1/7)	1	1/6 (1/6)	7 (8)	7 (8)
HGVs	1/5 (1/6)	1/5 (1/6)	6 (6)	1	9 (9)	9 (9)
Cyclists	*1/9 (1/9)*	*1/9 (1/9)*	1/7 (1/8)	1/9 (1/9)	1	*1 (1)*
Pedestrians	*1/9 (1/9)*	*1/9 (1/9)*	1/7 (1/8)	1/9 (1/9)	1 *(1)*	*1*

Table 52 Pair wise comparison matrix for 2nd level 3 hierarchy (group 4 results)

9.4.3.5 First family of criteria for evaluating bridge improvement works

Only one set of results is presented for the following, as these questions were asked directly of the interviewees, and therefore were not open to interpretation.

Group 1 Results	High Benefit	Medium Benefit	Low Benefit
High Benefit	1	7	9
Medium Benefit	1/7	1	2
Low Benefit	1/9	1/2	1

Table 53 Pair wise comparison matrix for the level 2 hierarchy (group 1 results)

Group 2 Results	High Benefit	Medium Benefit	Low Benefit
High Benefit	1	5	7
Medium Benefit	1/5	1	3
Low Benefit	1/7	1/3	1

Table 54 Pair wise comparison matrix for the level 2 hierarchy (group 2 results)

Group 3 Results	High Benefit	Medium Benefit	Low Benefit
High Benefit	1	3	6
Medium Benefit	1/3	1	3
Low Benefit	1/6	1/3	1

Table 55 Pair wise comparison matrix for the level 2 hierarchy (group 3 results)

Group 4 Results	High Benefit	Medium Benefit	Low Benefit
High Benefit	1	5	9
Medium Benefit	1/5	1	7
Low Benefit	1/9	1/7	1

Table 56 Pair wise comparison matrix for the level 2 hierarchy (group 4 results)

The first step in synthesising the judgements presented in this pair wise matrix is to reduce the matrix to a comparison vector. This is done by the Eigenvector method. The principal eigenvalue is first calculated (this also gives an indication of the level of consistency between answers), the corresponding Eigenvector gives an estimate of the relative preferences. The elements of this vector are then normalised to sum to unity. MathCad was used to carry out this analysis, as it had the capacity for matrix mathematics. A bi-product of this method is a measure of consistency between the elements of each pair wise comparison matrix. This is calculated as the relative deviation from the principal Eigenvector of each original element. The larger the relative deviation, the larger the inconsistency of the subjective opinion that generated the elements. The spreadsheets for these evaluations are shown in Appendix 6.

9.4.4 Reaching a consensus between experts

A set of relative weights was determined for each group interviewed. It was then necessary to combine the different sets of weights to produce a consensus set of weights. An algorithm, called the "modified median consensus algorithm" [159] was used for this purpose. However, this would have been useless if the different sets of weights were very diverse (e.g. due to wide variances in policy and culture within each authority). The modified median consensus algorithm therefore, also provides a measure of the group cohesiveness, to indicate how closely each of the individual experts agrees. The consensus was evaluated by using the following procedure for each family of criteria:

1. The scores for each interview group were placed in the columns of a table to form a matrix with the criteria as shown in Table 57 below:

	Group 1	Group 2	Group 3	Group 4
Risk of Failure	0.566	0.532	0.553	0.594
Social Impacts of Restrictions	0.236	0.21	0.271	0.225
Cost of Interim Measures	0.123	0.122	0.105	0.11
Cost of Strengthening	0.028	0.082	0.048	0.047
Bridge Improvements	0.048	0.053	0.022	0.023

Table 57 Matrix of results for each group for the top-level criteria

2. Each row of the table was then rearranged in ascending orders of the scores, as shown in Table 58 and each newly formed column was summed:

Risk of Failure	0.532	0.553	0.566	0.594
Social Impacts of Restrictions	0.21	0.225	0.236	0.271
Cost of Interim Measures	0.105	0.11	0.122	0.123
Cost of Strengthening	0.028	0.047	0.048	0.082
Bridge Improvements	0.022	0.023	0.048	0.053
Total	0.897	0.958	1.02	1.123

Table 58 Matrix of rearranged results for the top-level criteria

3. The final step was to interpolate between the two columns of score whose totals bracket a sum value of 1.0, i.e. between columns 2 and 3. This gave consensus weights as shown in Table 59.

Risk of Failure	0.56
Social Impacts of Restrictions	0.23
Cost of Interim Measures	0.12
Cost of Strengthening	0.05
Bridge Improvements	0.04

Table 59 Calculated consensus weights for the top-level criteria

The consensus weights and individual group weights for each family of criteria are presented in the next section for each group of criteria. All four decision groups arrived at similar weightings for most criteria despite different cultural and political viewpoints.

9.5 Discussion of the Results

Figure 28 to Figure 32 and Table 60 to Table 64 show the individual and consensus weights for each family of criteria for both the original and revisited (in parentheses) evaluations of interview responses. Figure 28 and Table 60 show the results for the top-level criteria used to determine the overall Bridge Priority Index. This shows a very close consensus of views from the different interviewees for both evaluations and between the two evaluations.

	Group 1	Group 2	Group 3	Group 4	Consensus
Risk of Failure	0.584 (0.566)	0.554 (0.532)	0.555 (0.553)	0.612 (0.594)	0.57 (0.56)
Social Impacts of Restrictions	0.233 (0.236)	0.224 (0.21)	0.254 (0.271)	0.212 (0.225)	0.23 (0.23)
Cost of Interim Measures	0.11 (0.123)	0.112 (0.122)	0.112 (0.105)	0.105 (0.11)	0.11 (0.12)
Cost of Strengthening	0.028 (0.028)	0.065 (0.082)	0.058 (0.048)	0.046 (0.047)	0.05 (0.05)
Bridge Improvements	0.045 (0.048)	0.045 (0.053)	0.02 (0.022)	0.025 (0.023)	0.04 (0.04)

Table 60 Individual and consensus weights for the top-level criteria "the bridge priority index" for the original and revisited evaluations of interview responses

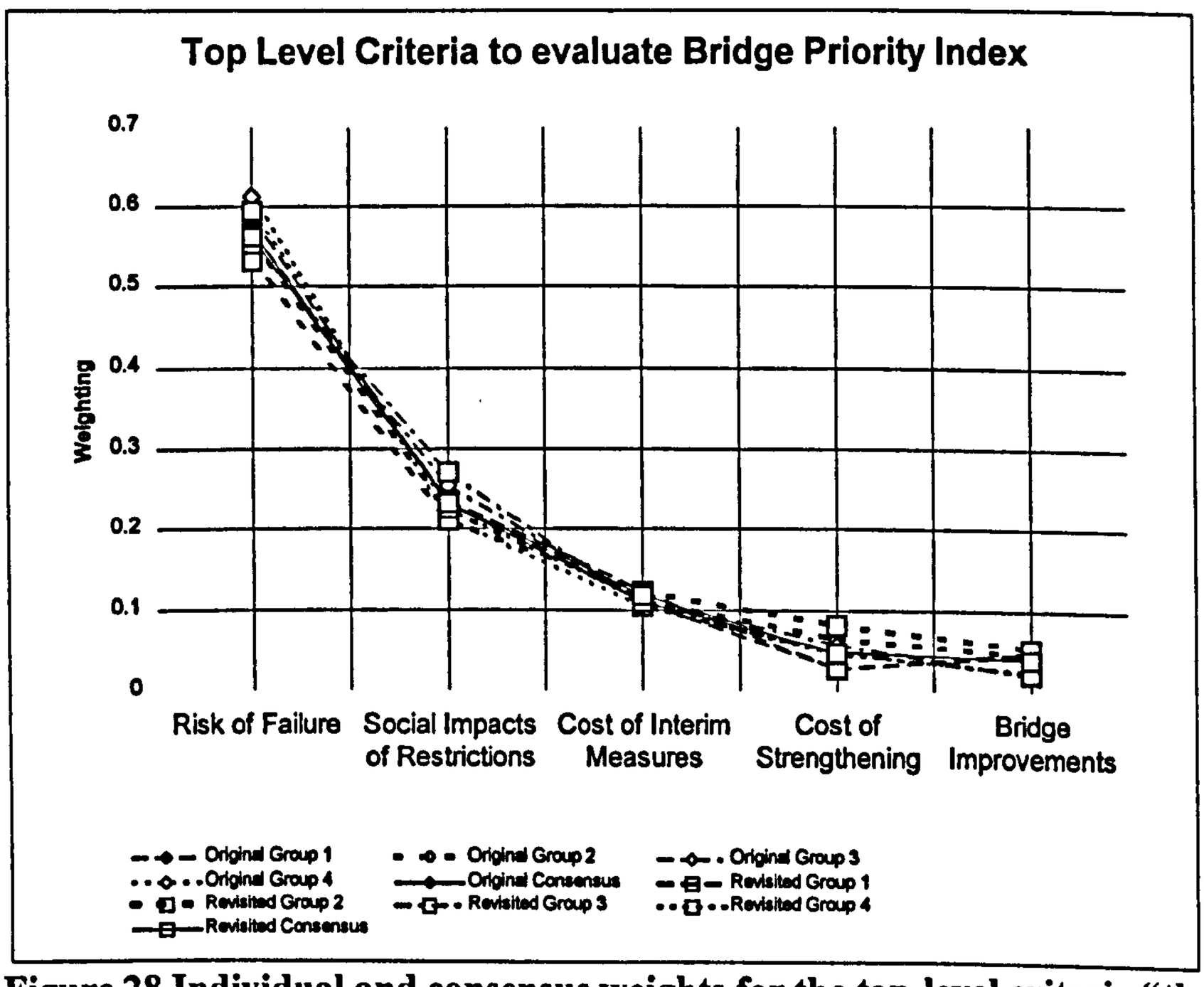


Figure 28 Individual and consensus weights for the top-level criteria "the bridge priority index" for the original and revisited evaluations of responses

Figure 29 and Table 61 show the results for the second level criteria used to determine the social impact of restrictions. Due to different interpretations of the criteria, this does not show a very close consensus of views from the different interviewees. After some discussion, it was agreed that it was very difficult to separate the two criteria and that they should be considered of equal importance. This then matched the predicted consensus weights.

	Group 1	Group 2	Group 3	Group 4	Consensus
Route Importance	0.25 (0.2)	0.833 (0.857)	0.143 (0.143)	0.75 (0.75)	0.50 (0.48)
Route Category	0.75 (0.8)	0.167 (0.143)	0.857 (0.857)	0.25 (0.25)	0.50 (0.53)

Table 61 Individual and consensus weights for the second-level criteria "the social impact of restrictions" for the original and revisited evaluations of responses

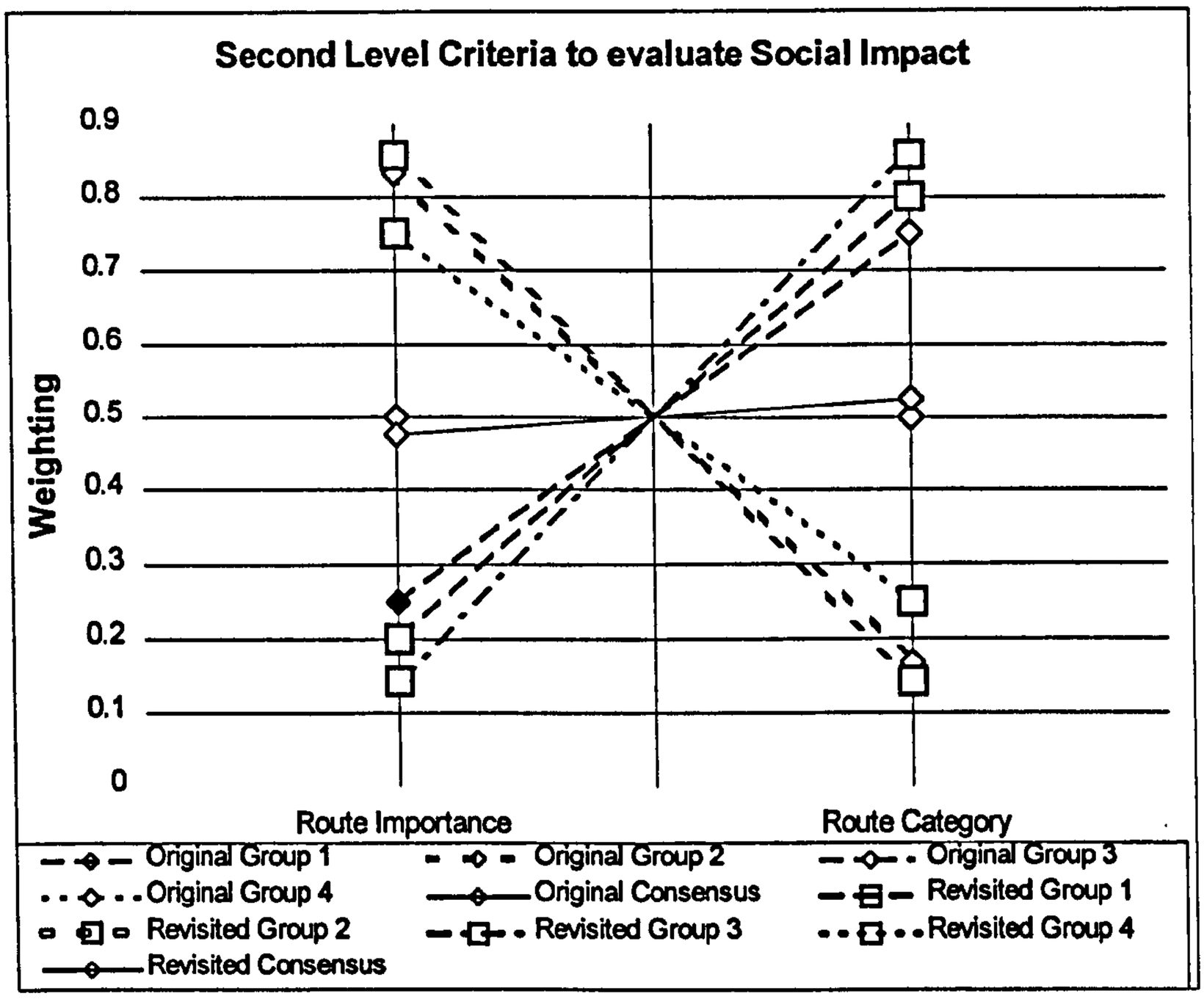


Figure 29 Individual and consensus weights for the second-level criteria "the social impact of restrictions" for the original and revisited evaluations of responses

Figure 30 and Table 62 show the results for the third level criteria used to determine the route category. This once more shows a very close consensus of views from the different interviewees.

	Group 1	Group 2	Group 3	Group 4	Consensus
Primary Route	0.429 (0.444)	0.429 (0.438)	0.438 (0.438)	0.438 (0.438)	0.43 (0.44)
Borough Principal Route	0.429 (0.444)	0.429 (0.437)	0.437 (0.437)	0.437 (0.437)	0.43 (0.44)
Local Distributor Route	0.071 (0.056)	0.071 (0.063)	0.063 (0.063)	0.063 (0.063)	0.07 (0.06)
Local Access Route	0.071 (0.056)	0.071 (0.062)	0.062 (0.062)	0.062 (0.062)	0.07 (0.06)

Table 62 Individual and consensus weights for the third-level criteria "the route category" for the original and revisited evaluations of responses

Figure 30 Individual and consensus weights for the third-level criteria "the route category" for the original and revisited evaluations of responses

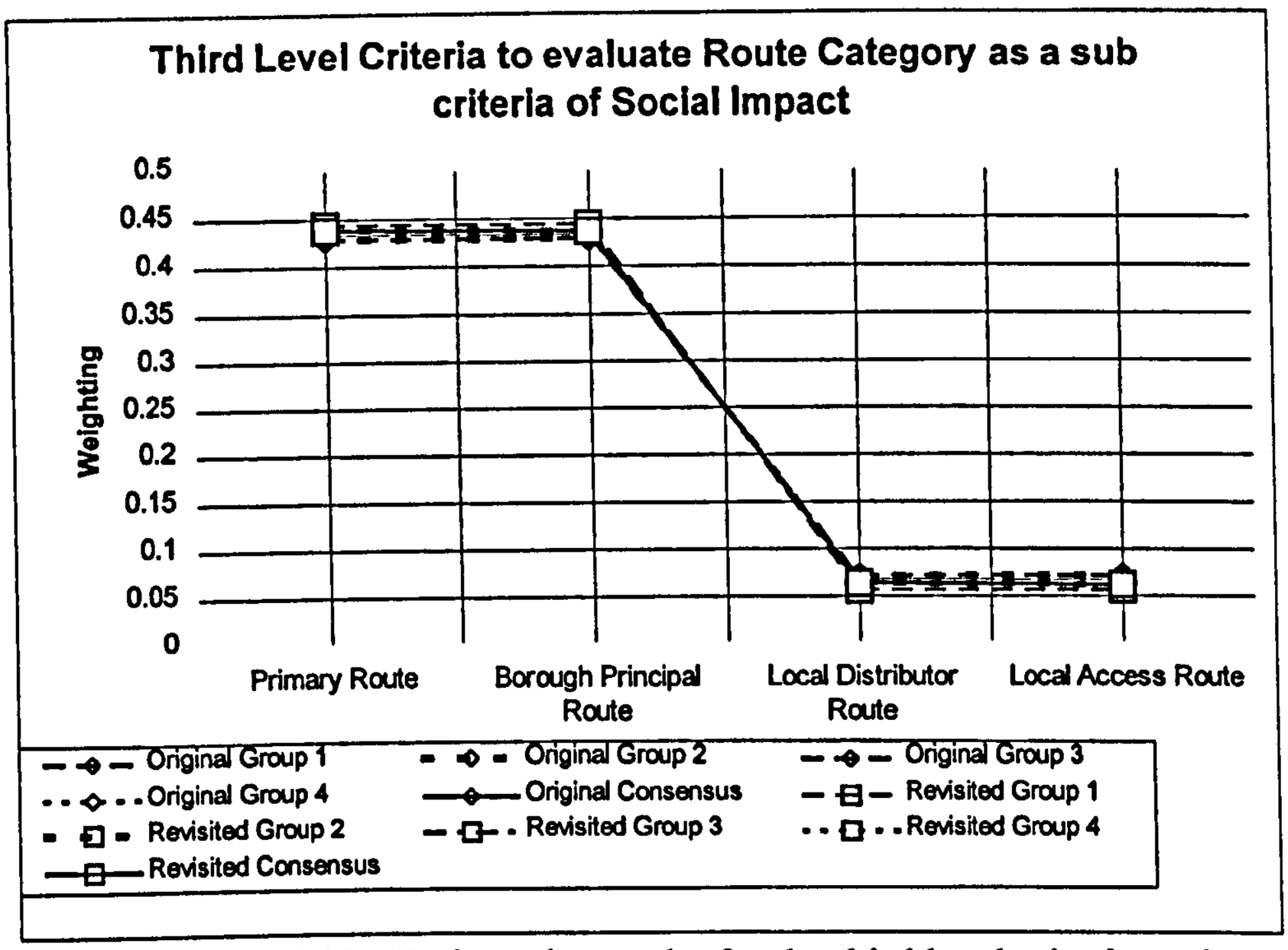


Figure 31 and Table 63 show the results for the third level criteria to determine the route importance. This shows another disagreement between interview groups. Post evaluation discussions showed that group 3 had misunderstood the implication of the questions for this criterion and asked for their results to be ignored. The other three groups' responses reflected the cultures of the regions that they represented. Groups 1 and 2 represented commerce dependent areas and so gave buses more importance than HGVs, while group 4 represented an industry dependent area giving HGVs more importance.

	Group 1	Group 2	Group 3	Group 4	Consensus
Fire Engines	0.336 (0.325)	0.359 (0.355)	0.101 (0.114)	0.361 (0.362)	0.34 (0.33)
Emergency Vehicles	0.336 (0.352)	0.359 (0.355)	0.101 (0.114)	0.361 (0.362)	0.34 (0.35)
Buses	0.178 (0.175)	0.16 (0.159)	0.366 (0.36)	0.072 (0.076)	0.16 (0.16)
HGVs	0.091 (0.094)	0.074 (0.081)	0.366 (0.36)	0.163 (0.157)	0.10 (0.11)
Cyclists	0.034 (0.031)	0.027 (0.029)	0.037 (0.03)	0.022 (0.021)	0.03 (0.03)
Pedestrians	0.024 (0.023)	0.021 (0.021)	0.027 (0.022)	0.022 (0.021)	0.02 (0.02)

Table 63 Individual and consensus weights for the third-level criteria evaluating the route importance for original & revisited evaluations of interview responses

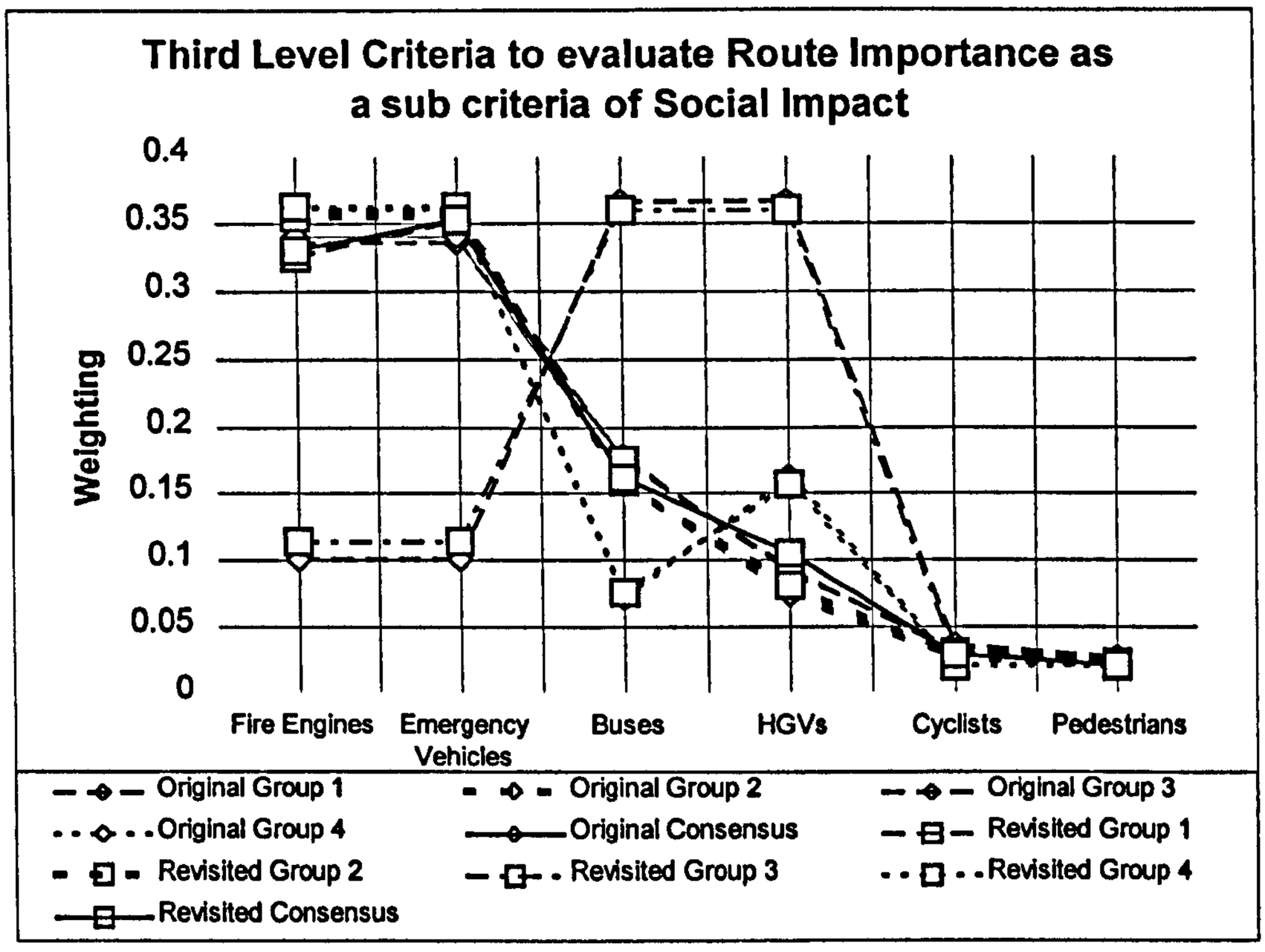


Figure 31 Individual and consensus results of the weights for the third-level criteria evaluating route importance for original & revisited evaluations of interview responses

Finally, Figure 32 and Table 64 show the results for the second level criteria used to determine the bridge improvement benefits for the original and revisited (in parentheses) evaluations of interview responses. This shows a very close consensus of views from the different interviewees both between interviewees and between evaluations.

	Group 1	Group 2	Group 3	Group 4	Consensus
High benefit	0.793 (0.793)	0.731 (0.731)	0.655 (0.655)	0.722 (0.722)	0.72 (0.72)
Medium benefit	0.131 (0.131)	0.188 (0.188)	0.25 (0.25)	0.227 (0.227)	0.20 (0.20)
Low benefit	0.076 (0.076)	0.081 (0.081)	0.095 (0.095)	0.051 (0.051)	0.08 (0.08)

Table 64 Individual and consensus results of the weights for the second-level criteria to evaluate the bridge improvement benefits for the original and revisited evaluations of interview responses

These consensus weights were then put forward to be used in the actual evaluation of the alternative bridges requiring strengthening work.

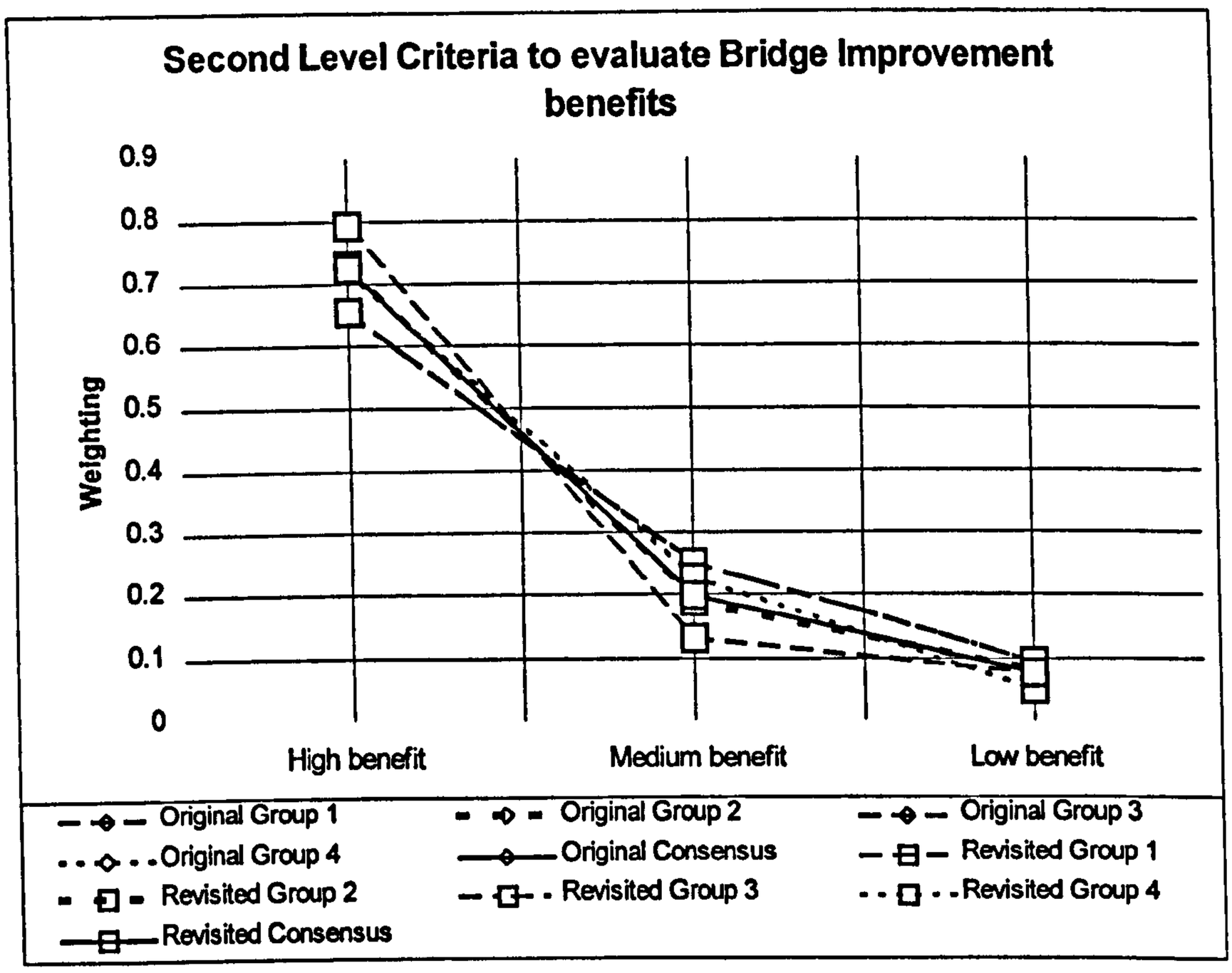


Figure 32 Individual and consensus results of the weights for the second-level criteria to evaluate the bridge improvement benefits for the original and revisited evaluations of interview responses

9.6 Selection of "Best" Alternative

Before a decision could be made between the different alternatives, the scores for each of the main factors had to be transferred to a common scale. If the attributes were valued in their simplest units (e.g. cost of strengthening and cost of interim measures in pounds, risk in the form of a function of pounds, social impact and bridge improvements in the form of a subjective score), then it is very difficult to evaluate the trade-offs between them i.e. comparing money with lives lost.

Each score had to be mapped onto a scale from 0 to 100 to represent the performance of the specific bridge strengthening project under consideration according to each factor.

For each of the main factors the worst imaginable score for that factor was assigned a zero and the best imaginable was assigned a 100. For each factor, a linear (or logarithmic) relationship was then defined between the calculated score and the performance rating. This section of the work was carried out predominantly by another member of the project team, with some support, advice and ideas from me. For this

reason, it is not described fully here. Once the performance ratings had been determined for each of the main factors, the overall priority score was calculated by summing the products of the importance weightings and the performance weightings for each factor. The overall priority scores for each bridge strengthening project under consideration could then be considered to allow project selection. The final order of priority of the bridges requiring strengthening work was commercially sensitive information that has been withheld by WS Atkins.

9.7 Conclusions

The problem addressed in this case study was extremely political and contentious in nature. A large number of stakeholders were involved in and affected by the decision. Therefore, all voices were trying to be heard. The problem was further complicated by the significant uncertainties involved in the integrity assessments of the large number of bridges and the consequences of bridge failure. Furthermore, the decision had to be made with as much consensus as possible in a very short time-scale.

This meant that the stakeholders were a very significant issue to be addressed in the decision-making. To address this problem, I interviewed representatives of all stakeholder groups as an independent third party to identify their preferences so that these could be built into a consensus and used to help solve the decision problem. The weights achieved for the four groups were very consistent. This showed agreement across the stakeholder groups of the important factors to be considered when allocating resources to bridge strengthening. All parties that were interviewed agreed that the risk of the bridges failing in service was the most significant factor to be considered when prioritising between bridges. This process helped the stakeholder groups explore the problem and come to a more detailed understanding of the important factors. It also provided a clear means for building consensus between the conflicting stakeholder groups.

The alternatives in this decision were the more than 150 bridges that required strengthening. However, there was the possibility that more than one bridge could be selected to ensure best use of the allocated budgets. Therefore, the number of alternatives was far more than the number of bridges requiring repair as a large number of combinations of bridges could also be selected. This vast series of alternatives therefore meant a very thorough investigation of the problem could be carried out with a better chance of identifying the best option.

The decision criteria were identified very early on in the analysis by interviewing experienced bridge engineers and other council representatives who represented the views of external stakeholders. A comprehensive list of factors was produced and this was then refined and condensed through discussions with other boroughs. The main criteria on which the bridge prioritisation decision was to be based were therefore:

- The cost of carrying out strengthening work
- The risk of bridge failure if strengthening work is not carried out

- The cost of interim measures such weight restrictions, or propping if strengthening work is not carried out immediately,
- The impacts on the local society if the work is not carried out
- The additional benefits that can be gained by carrying out bridge improvement and upgrading works at the same time.

These criteria were measured in their most natural units to ensure clear communication of the decision process, and a clear audit trail to prove the systematic and unbiased manner in which the decision was made. This again promoted understanding and ownership of the decision by all stakeholders.

Structural analysis was used to construct an influence diagram of the problem, which helped elicit the important issues to be addressed from discussions with the different stakeholder groups. However, the most benefit to the decision in terms of structural analysis came from developing the hierarchy of criteria, which helped in the measurement of the alternatives in terms of each criterion. It also helped in the identification and quantification of preferences between the criteria. This also promoted understanding and ownership of the decision by all stakeholders.

The information that was required to help solve the decision problem was identified through the help of the criteria hierarchies developed previously for each bridge requiring strengthening. A questionnaire was constructed to help each borough bridge engineer evaluate each bridge against the given criteria for the list of bridges requiring strengthening work in their boroughs that they had identified. For most of the criteria, this questionnaire was as thorough as possible, gathering as much real and relevant data as possible.

However, due to the limited information available for each bridge in terms of the structural assessment of the bridge and due to the tight time-scale, the method for evaluating risk had to be simplified. The idea of the risk index was introduced as a representative value embodying as much information as possible in the risk evaluation. This was sufficient for the decision-making at hand and ensured all bridges were treated fairly and evaluated against risk consistently. However, risk was found to be the most important decision factor. It was therefore felt that a more rigorous evaluation of risk for the bridges at the top of the prioritisation list could provide "finer tuning" of the final ranking. The risk evaluation that was carried out was an integral part of the decision process and the importance of the risk in the decision reflected the importance placed on it by the stakeholders.

As mentioned above these importances were assessed by interviewing representatives of all stakeholder groups as an independent third party. This was the first time that the analytic hierarchy process had been used to rank bridges according to multiple criteria. A new method for eliciting preferences from bridge managers based on Saaty's pair wise comparisons was developed to make the method more user friendly and therefore more accessible to all bridge engineers. The individual importances were then built into a consensus through mathematical models and further group discussion and used to help

solve the decision problem. The weights achieved for the four groups were very consistent. This showed agreement across the stakeholder groups of the important factors to be considered when allocating resources to bridge strengthening. This interview and discussion process helped the stakeholder groups explore the problem and come to a more detailed understanding of the important factors. It also provided a clear means for building consensus between the conflicting stakeholder groups. The presence of the third party facilitator ensured that the stakeholders understood the decision problem in an unbiased manner giving confidence to the stakeholders that their viewpoints would be fully represented. The set of consensus importances were then used to weight the criteria and hence the scores for each bridge, thus fully integrating the stakeholder preferences into the decision process in a clear, auditable and logical manner.

Sensitivity analysis was carried out to evaluate the robustness of the method adopted for interpreting the interview results. This showed very little difference on the consensus weightings even using the extremes of the interpretation bands. This showed that consensus was robust and logical, which further encouraged ownership of the results by the stakeholder groups.

Of the two bridges recommended by the decision process for immediate strengthening, one was completely expected by all parties, the other was not. However, detailed consideration of the latter bridge against the decision criteria showed that it was the logical second choice. Therefore, since all stakeholders had been involved so thoroughly in the decision process and hence agreed to its logic, they agreed to the logic of the decision.

The use of the risk-based decision model meant that risk was clearly accounted for in the decision that was made. It is very likely that in the absence of such a model, normal practice would have been to evaluate the alternatives based on cost and possibly load capacity only. This would not have been able to single out one or two bridges as top priority and therefore would not have solved the problem. The risks involved are significant and therefore have a significant impact on the final decision.

The application of the risk-based decision model to this case study has showed that for this decision all stages of the process were relevant and helpful. Some of the important issues in this decision may not have automatically been identified and accounted for, however the decision process prompted thorough investigation of every issue ensuring the decision was as thorough and robust as possible. For this decision, however, the originally defined structural analysis in terms of developing a decision tree or an influence diagram, was not particularly helpful. A decision tree would have been unmanageable in size and the influence diagram shed little additional light on the problem. However, by extending the definition of structural analysis to include the development of criteria hierarchies this stage in the process became probably one of the most valuable in terms of developing understanding and consensus.

The use of a structured decision process to support the decision in this case helped the stakeholders identify the most important issues to be addressed and allowed the

important decision criteria and alternatives to be identified, agreed and ranked. It also supported the understanding of other's opinions and perceptions and helped build consensus in the final decision. The decision process also allowed the important data on which the decision should be based to be identified and gathered in an accessible but meaningful form.

The use of the risk-based decision model brought the significance of the risks to the fore and meant that the assessment of risks was an integral part of the decision process. The consideration of all of these issues meant that a clear audit trail could be produced of the way the decision was made. This could then be re-visited, understood and if necessary re-addressed at a later stage.

10 CASE STUDY 5

REVIEW OF RISK-BASED DECISION-MAKING IN APA

10.1 Introduction

APA normally becomes involved in engineering decision-making after the high value field development (concept selection) decisions have been made. The operator has already determined decisions such as the field development type, the pipeline requirement and sometimes even the pipeline operating conditions before APA are commissioned to design the pipelines. Therefore APA is left with the lower value, lower complexity decisions in preliminary and detailed pipeline design. The earlier decisions made by the operator and the contract strategy can severely restrict the way design decisions are made by APA, causing APA to produce, at times, sub-optimal designs and restricting their contribution to high value decisions. This can cause problems for the client or operator and reflect badly on APA. This document reviews some risk-based decisions made in preliminary engineering design at APA, when the decision-maker is faced with the most significant risks and consequences to be endured for the structure's remaining life. The objectives of this case study were:

- To identify the types of engineering decisions made by APA now and in the past, and the types of decisions made by others that APA would like to make.
- To compare the decisions with the methods developed within this research.
- To draw conclusions on how reality can be improved to take advantage of theory.

A number of recent engineering projects were identified and reviewed in detail to establish the types of engineering decisions that APA generally make. Also identified were the decisions that APA did not make that were made already by the contractor or the operator. For every key decision, an indication of the main decision-makers, the important decision criteria and any constraints on the decision were identified.

Some of APA's senior engineers and managers were interviewed about how they made these decisions. In addition, more general questions were asked on the usual approach to engineering decision-making. The interview outline used is presented in Appendix 7. The following discussion describes the types of decisions made throughout the stages of a pipeline design and management life cycle and the discussion is illustrated with examples of some of the real life decisions identified and evaluated through the interviews.

10.2 Life Cycle Decision-making

The following identifies the typical stages of a pipeline's life cycle and discusses some of the typical decisions faced at each stage. Brief mention is also made of some of the decisions investigated in detail through the desktop study and interviews.

10.2.1 Field identification

The need or opportunity for an investment in a structural asset has to be identified or justified before it can be approved. In the oil and gas industry, the need or opportunity

to produce oil and/or gas from a new field development has to be justified before field development options can be investigated. Decisions at this stage are taken at a high level in the operator's organisational structure with some degree of expert advice from in-house specialists and external consultants. The key tasks for the decision maker in these situations are to establish the extent of oil/gas reserves in the field and to identify any potential risks associated with its economical extraction. Time spent identifying any unknowns/uncertainties and trying to evaluate these can significantly support any decision-making. The decisions made at this stage are based on limited data, subjective judgements and predictions of capacity, turnover, whole life cost and profit.

APA do not tend to be involved in decisions at this stage, therefore it is not considered appropriate to elaborate any further on this stage here.

10.2.2 Feasibility assessment

Having identified a field with a potential for development, it is then necessary to determine the technical feasibility of the possible development scenarios. Of interest to APA at this stage would be the feasibility assessment of the available options for transporting produced gas/oil from the field, which could include the use of a tanker or a subsea pipeline tied in to an existing trunk line. At this stage the decision-making would still be controlled by the operator, although consultants like APA may be asked to provide expert advice, or supporting assessments to aid the feasibility assessment. Significant uncertainty would still be involved at this stage, for example, in the design capacity, in potential environmental impacts, etc. One significant task at this stage, therefore, would be to validate the reserve levels, before excessive expense is made.

As with the previous stage, APA do not tend to be involved in decisions made at this stage apart from producing supporting calculations and offering expert advice.

10.2.3 Conceptual design

Conceptual design is the time when the preferred development option is selected based on the results of the feasibility assessment. For example, if the pipeline concept was found to be most feasible, then the important issues to be considered here would include the method and location of pipeline tie in and the proposed capacity. During this stage the design proposal is developed, to identify all key design features to be incorporated in the detailed design so that the detailed design can be put out to tender with the operator confident of receiving a design that meets all the necessary requirements.

Although APA are not often involved at this stage, the results of the decisions made can be observed from the project work performed by APA. For example, in two of the projects investigated, the operator had already carried out the conceptual design and had identified the use of a pipeline as the most appropriate transportation method. In one of the projects it had already been decided to develop the wells subsea then to tie them back by subsea flowlines to a new platform located adjacent, and bridge linked, to a second platform. Flowline lengths from the two satellite wells had also been established. In addition to the flowlines, the development included wellhead protection

structures and electro-hydraulic multiplexed control umbilicals between the platform and satellite wells.

In the second project, the operator had decided to install a new export pipeline to replace the existing line, to a different platform owned by a different third party operator who had offered to transport the oil at a lower tariff. According to Interviewee 3, "*the original line had been buried under a mountain of rock, so the operator wanted to leave this pipeline on the seabed. The operator worked on a conceptual study to demonstrate that the line could be left on the seabed.*"

The third project involved an operator who wanted to expand a transmission pipeline to accommodate increased throughput from third party operators, which was originally available through a number of pipeline 'Tees'. The whole purpose of this project was therefore to carry out a conceptual study of the proposal to install a new parallel loop over a length of the line. This would be carried out by first installing a new tee, to provide the upstream connection for the new loop and to select an appropriate existing tie-in point for the downstream connection. The loop would increase the main transmission line capacity but a series of detailed process analyses were required to evaluate the available flow rates from the various original third party entrants to the pipeline system. Then a hydraulic and thermal analysis evaluated the flow capacity that may be obtained at various positions along the pipeline system, for a range of loop lengths and diameters. As Interviewee 1 said, "*the operator gave us the conceptual work to look at where the gas was coming from, what flow rates and pressures, and so what diameter of pipeline should be used for the detailed design.*"

On the project management side, the conceptual design stage would also involve the operator obtaining agreement in principal to commercial issues and determining the appropriate contracting strategy for awarding the detailed design and installation work. In recent years, the trend has been for operators to award "EPIC" contracts to installation contractors to Engineer, Procure, Install and Commission the installation for a fixed fee. Any design work that the installation contractor is unable to perform would then be sub-contracted to design consultants such as APA.

The first two projects described above were carried as EPIC contracts within which APA was subcontracted to the installation contractor to carry out the design work. The third project, following the conceptual design stage, was put out to tender to carry out the front-end engineering phase. According to Interviewee 7, "*Two installation contractors decided to bid jointly and asked us to bid to them. The project was set up with a conceptual phase and a detailed design phase, still within the FEED. At the end of this we were to have a well-defined design that could be costed correctly.*" This would then have allowed the development work to be awarded as an EPIC contract had it continued.

10.2.4 Preliminary/front end engineering design (FEED)

The preliminary or front end engineering design phase involves making a number of influential design decisions which then dictate the way the detailed design will be

carried out. These decisions could typically include the routing of the pipeline, the diameter and wall thickness of the line pipe, the locations of spools and crossings, types of valves and pigging facilities, methods for protecting the spools and valves, pipeline coatings and other corrosion inhibitors.

For the first project, APA was employed by the operator to carry out the preliminary design engineering (front-end engineering) including providing subsea control services on a reimbursable basis with an upper budget limit. The issues addressed included carrying out the initial hydraulic analysis and designing the pipeline route.

The hydraulic analysis was carried out based on the best estimates of operational and design temperature as the upper bound for the mechanical design. This was a risk but no well data was available. If the pipeline was designed for too high a temperature then the design, procurement and installation cost would be excessive. If the pipeline was designed for too low a temperature then the operational conditions would have to be reduced to keep the pipe from failing. This could increase the corrosion problems and stop the field from being cost-effective.

APA designed the pipeline route to avoid a region of significant sand waves which would have been encountered had a straight line been taken. According to interviewee 2, "*during the front end engineering work APA recommend avoiding the sand waves on the basis that it was considered the lowest cost option.*"

The front-end engineering work for the third project involved a number of analyses and decisions in order to determine the suitability of carrying this project through to contract award. These issues included selecting the best pipeline expansion loop configuration. This included the loop length and route and the valving requirements to allow safe hot tap operation, independent isolation of the loop and pigging. It also involved identifying the best protection solution at the tie-in point.

The second project moved straight from conceptual design to detailed design via an EPIC contract.

10.2.5 Bid engineering

At the bid engineering stage, the decision-making moves initially to the prospective installation contractors who, in EPIC contracts, have to identify a suitable method of approach and evaluate a fixed price at which to bid the work. To aid them in their decision-making, they will do some preliminary analyses. These could include identifying a suitable pipe wall thickness (so that pipe costs can be calculated) and evaluating the propensity for upheaval buckling and the critical span length (so that post installation mitigation costs can be calculated). Design consultants such as APA are required to run preliminary analyses at this stage to provide "ball park" figures to support the contractor's decision-making. Furthermore, they are required to bid to the contractors to receive the design work, if the contractor wins the overall contract. The contractor therefore has to make decisions concerning the design and installation strategy and the bidding strategy (e.g. low cost–low risk or high cost high risk) at this stage.

APA has contributed to the bid engineering for a number of different contractors and development projects. These usually include confirming the best diameter pipeline to meet the required flow rate base on the proposed operating conditions. They also consider the proposed wall thickness and operating conditions to determine the propensity for upheaval buckling and the stability of the pipeline on the seabed.

10.2.6 Contract award

Once the contractors have submitted their bids to the operator, the operator has to make a very significant decision – who to award the contract to. The impact of this decision, good or bad, can reach throughout the whole life of the field development.

In the first project, the operator decided to progress the detailed design in the form of an EPIC contract as a way of controlling costs and risk as the costs of the conceptual design had risen out of control. However, such a contract restricts the communication process between the operator, the contractor and the design consultant due to the way all decision-making power is handed over to the installation contractor with the EPIC contract. In this project, this meant that APA was not able to rationally support the operator in their design decision-making.

In the second project, the operator invited bids for EPIC contract to design and install a pipeline on the seabed. However, the installation contractor selected by the operator could not guarantee to install a pipeline on the seabed. This is because they could only reel lay pipe and therefore could not use concrete coating (which had been the basis for most of the conceptual design assessment). Because of the low cost installation method, they were the most competitive on price and therefore won the work. However, they could not achieve the conceptual design. As interviewee 2 said, "*the contractor had bid for the work saying, "this is our price for an untrenched pipeline, but if in the remote chance our consultant tells us that it does need to be trenched, then this will be additional to our bid price"*." At this late stage, the operator had some checks done and initiated some testing which suggested that installing a non-concrete coated pipe could work. Thus in the belief that concrete coated pipe and uncoated pipe were similar, the operator had evaluated all the bids based on not trenching and therefore, according to interviewee 2, did not take into account the real cost of this contractor's bid.

In the third project, the FEED stage was put out to tender and the operator awarded the work to two installation contractors who had decided to bring an edge to their proposal by bidding it as a joint venture. They then carried out the work as an integrated project team consisting of the operator, the two main contractors, APA as a design consultant and a couple of other contractors/consultants.

10.2.7 Detailed design

By the detailed design stage, the investment has been estimated and nearly approved. This stage aims to design the pipeline for safety and whole life cost through the selection of dimensions and materials suitable 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

operating conditions and as built conditions), and more by engineering predictions of safety, based on detailed analysis, specification of appropriate equipment and testing.

This is one of the most significant stages in the pipeline life cycle for APA (in terms of revenue) and they are able to contribute to the decision-making concerning the finer detail of the design. However, there is no doubt that these are lower value decisions.

In the first project reviewed, the main decisions made at this stage included finalising the pipeline route and dimensions. However, as soon as the EPIC contract was awarded, the chosen contractor recommended changing the pipeline route from that identified at the FEED stage to run through the sand waves hence reducing line pipe costs. They recommended that it would be more cost effective to trench through the sand waves after laying the pipeline and then mitigate for any remaining out of straightness features, rather than pre-sweep and dredge before pipe lay. The operator agreed to take on the risk of the mitigation costs. In other words, despite being involved at the FEED and detailed design stages; the decisions were made without reference to APA.

In the second project, the contractor who won the EPIC contract awarded APA a fixed price contract to undertake detailed design of the subsea pipeline system. The contractor had already specified the line pipe and APA was asked to verify the suitability of this selection. However, there was no opportunity to optimise the design since the line pipe had already been ordered. According to Interviewee 3, "*In order to keep their costs to a minimum, the contractor chose the minimum wall thickness that they could get away with. A thicker pipe wall would have been more robust and may have allowed them to leave the pipeline on the seabed, but that would have increased steel costs.*

Interviewee 3 said, "*We were tasked to look at the feasibility of leaving the pipeline on the seabed. This included the acceptability of the likelihood and consequences of the pipe being hit by fishing gear. The operator gave us a set of test results showing the feasibility of leaving a concrete coated pipe on the seabed but with inconclusive tests for a non-coated pipe. We had a meeting with the contractor who asked us whether the pipeline could remain untrenched. We thought not, but we did the calculations to verify this. However you looked at it, a large number of vessel crossings were going to occur. In fact, the entire route survey already showed evidence of trawl scars. The operator had proposed 60-70 start-ups and shutdowns a year. The likelihood of a leak was calculated as 1/100 and that was ignoring the likelihood of dents on welds or kinked dents. We would have left the operator a legacy of inspecting the pipeline every year.*" The operator finally agreed to trench the pipeline.

APA was then asked to design the trenched pipeline. Interviewee 4 said, "*the contractor bid a very low price for rock based on it having minimal insulation effect on the line. However, the operator's independent design work found this wasn't the case.*" The insulating effect of the trench would, therefore keep the temperature higher in the pipeline for longer, increasing the propensity for upheaval buckling. As Interviewee 3 said, "*to mitigate against buckling required huge amounts of rock which further*

increased the temperature. The potentially large requirement of rock would be a direct cost to the contractor."

Interviewee 3 said, "*we thought of every possible method to mitigate against upheaval buckling, but the contractor was only prepared to consider some options, which were passed to the operator for comment. The other alternatives were rejected because they involved increasing the pipe-lay costs, intermittent rock cover, or making the pipe thicker. All these were removed from the list before the operator saw them. The contractor wanted to minimise their own costs."* Therefore, APA investigated a limited range of cooling solutions. These included applying a flame sprayed aluminium coating on the spool piece, use of FBE coated pipe, PP coating and half moon shaped cooling fins attached to the top half of the spool piece. Interviewee 3 said, "*the calculations were driven to maximise the temperature drop with no consideration of the operability.*"

The contractor decided on a flame sprayed aluminium coated spool designed to drop 30degC over the spool piece. This removed most of the big upheaval buckling problems and brought the contractor back to their base cost.

10.2.8 Manufacture/procurement

At this stage, the proposed design and the investment have been approved. Fewer decisions are required here, but they are still significant and can be heavily influenced by different stakeholders (e.g. preference for certain contractors/suppliers). APA would not normally be involved at this stage unless the installation contractor required expert advice on materials and fabrication specifications.

10.2.9 Installation

The decisions concerning the installation and construction schedule are very important. They govern the timeliness and 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. These decisions would be initially made by the operator to establish an overall schedule for first production; however, the installation contractor would decide the finer detail of how this is achieved. APA would not be involved at this stage.

10.2.10 Pre-operation testing and inspection

Pipelines can be exposed to a higher than average probability of failure when they are hydrotested before commissioning. 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. In addition to the hydrotest, inspections are carried out following installation to evaluate the as-built condition of the pipeline. This would normally identify any dents, buckles, spans or other subsea features, which could affect the integrity of the pipeline. If the hydrotest or the inspection identified any defects

then it would be necessary to make decisions concerning any required remedial actions and the fitness for purpose of the pipeline. APA can become involved in supporting these decisions with the relevant engineering analysis.

For example, in the first project, APA carried out an Out of Straightness analysis after the lines had been laid. This calculated the amount of rock cover required to mitigate against upheaval buckling of the pipeline at places where the seabed was uneven. However, the measurements were taken less frequently than required and were also very noisy making it difficult to identify the true measurements. These factors led to a very conservative upheaval buckling assessment. This can mean even more mitigation costs.

Interviewee 3 was not happy with this situation saying, "*we ended up designing upheaval buckling mitigation within the sand waves, but sand waves move so what is mitigated now may not need mitigation in 2 years time. The sand waves won't be where they were, but somewhere else and need mitigation of spanning or buckling there.*"

10.2.11 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. Maintenance strategies have to be decided to minimise downtime and costs. These decisions are affected by uncertainties in inspection results and deterioration models. At the design stage, it is common practice to incorporate an inspection, maintenance and repair strategy to manage the whole life integrity and fitness for purpose of the pipeline. This can then be updated through the pipeline's life based on the results of each inspection and maintenance action undertaken. APA have been involved in both recommending suitable IMR strategies and in updating the strategies based on new results.

10.2.12 Requalification/life extension

When a pipeline is requalified, its design is reassessed under changed design conditions. This may be initiated by changes in operational parameters, excessive deterioration, unexpected damage, such as cracks, 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. The decision maker would be the operator at this stage, but would also be affected by the opinions of the regulatory authorities and consultants such as APA (who could be required to carry out a remnant life assessment to support the decision-making).

10.2.13 Decommissioning

When a structure is no longer required for operations, it has to be decommissioned. The main objective of decommissioning is to take the structure out of operation to a safe state. Uncertainties in the current condition, environmental conditions and future requirements have to be accounted for. Although the operator is the decision maker in this situation they will be very heavily influenced but the regulatory authorities, environmental groups and the government, who will often have very strict decommissioning policies. Design consultants such as APA can be brought in at this

stage to provide supporting analysis to the decision-making to ensure all stakeholders are satisfied.

10.2.14 Project management

At every stage in the life cycle, the work carried out by APA also involves important project management decisions. These decisions can affect the effectiveness of the design work, the influence of APA in the design decisions and the overall success (in terms of cost and schedule) of the project.

For example, in the first project APA identified a very experienced engineer to be their project manager for the FEED stage, according to interviewee 2, "*in recognition of his relationship with the operator's project manager.*" Although it is also believed that there was no one else available to take the responsibility. According to interviewee 1, "*the job was structured and bid with 4 very experienced engineers, who were unfortunately all contract personnel, which was not cost-effective and was difficult to control.*" The work was expected to expand to other fields and other developments, and so it was a strategic decision.

However, according to interviewee 2, "*there was a mismatch of expectations between APA's project manager and the operator with regards to the level of analysis detail required and so it became very difficult to control the project execution and relationships became strained.*"

Because of this problem, APA became behind on invoicing. The operator was unaware of the cost build up and APA did not notice that it had exceeded the original budget until an additional 30%was charged. These issues affected the relationship with the operator for the remainder of the design project.

In the third project, APA was invited to join their own project team with the overall integrated project team based full time at one of the contractor's offices. APA management decided that this was not a cost-effective option due to the additional costs of transporting staff to the offices and the amount of time that the team would not be paid on the project and yet could not be made reimbursable to other work. APA's project team therefore participated on an "ad hoc" basis according to the client's requirements. However interviewee 7 believed that, "*ideally APA should have sent people full time to the integrated project team to allow a more significant input to project decisions.*"

10.3 An Evaluation of Real-life Decision-making in APA

The following discussion compares the real life decisions made within APA with the proposed risk-based decision process developed as part of this research. General conclusions from the detailed project evaluations and interviews are drawn with examples to illustrate the discussion. Quotes from interviews are presented in italics.

10.3.1 Identify problem or opportunity

Common sense suggests that the first task in evaluating a decision problem is to identify what the problem is. It does not take much insight to sense the waste, inefficiency and

difficulties for the decision-maker if the basic need that the decision is to fulfil is not identified and understood.

Without the knowledge or experience of the proposed decision process, decisions can be made subconsciously, without even realising at times that a decision is required. This problem is more pronounced in project management decisions, where "non-decisions" are made by "drifting" into a solution of an unidentified problem. In these situations, the decision-maker often has no awareness or understanding of the problem or opportunity that lies before him/her and therefore does not recognise the alternative solutions available to maximise the benefit from the situation.

An example of this was the decision, in the third project, to withhold project members from full participation into the integrated project team. It appears that this was more of a non-decision because of the management wanting to avoid the logistical problems of seconding staff out of the office. It is unlikely that the management made a definite decision to limit their influence to the project team. The question can even be raised of whether the right problem was addressed. The problem that was addressed was how to maximise the project margin with minimum disruption to other projects. If the problem had been identified as how to best contribute to this project, at maximum margin and minimum disruption to other projects, then other alternatives may have arisen.

A similar issue arose in the first project, in the decision to select a project manager for APA's engineering work, which was how the problem was identified. However, it can be argued that the real problem was how to best meet the client's needs at maximum profit without disrupting other projects or clients.

Some project management decisions were, however, more clearly identified such as the need for the operator to control costs and risks by awarding the project as an EPIC contract in the first and second projects.

This situation is less severe for the design decisions, as there is more frequently a recognised engineering problem to be solved, which is recognised by the design engineer responsible. For example in the first project the process engineers identified the need to clearly identify the basis of the design in terms of expected operating temperatures, whether best estimates should be used or more detailed data gathering should be carried out. Also the decision concerning the routing of the pipeline was clearly identified both at the conceptual design stage and readdressed at the detailed design stage, due to the impact it would have on the rest of the pipeline design. In the second project the key design decisions were determining the pipeline wall thickness, determining whether the pipeline should be trenched or not and identifying a suitable cooling system for the pipeline to prevent upheaval buckling. As will be discussed later, if the second decision had been made before the first, then the third decision may not have been necessary. This is because the third decision addresses the problem that arose from the decision to trench the pipeline and the decision to trench the pipeline arose from selecting a minimum wall thickness. The trench would insulate the pipeline, maintaining its temperature for longer, increasing the propensity for upheaval buckling.

In the third project, due to the conceptual nature of the work each decision was very clearly identified and evaluated. The main decisions here were identifying what pipe diameter the expansion loop should be, selecting the best pipeline expansion loop configuration including the loop length and route and the valving requirements to allow safe hot tap operation, independent isolation of the loop and pigging.

10.3.2 Identify stakeholders in the decision

There are very few decisions that should be reached by a single decision-maker with total disregard for others' views and so often, if they are, they result in poor decisions. Even where the formal procedures of an organisation dictate that an individual has responsibility for making the decision, the views of interested parties usually need to be accounted for. On a formal level, a committee can be formed consisting of representatives for different interests. Committees may still, however be influenced by other external parties who would also need to be consulted. This results in all members of the decision body (whether a committee or a set of independent advisors) having different degrees of influence in the decision. The decision body also interprets the organisation's objectives into evaluation criteria, which means that the decision stakeholders not only make the choice itself but can also control the options and information considered.

However, the absence of the decision process in the real life decisions evaluated here meant that quite often, the best solution was not sought on behalf of all stakeholders. This problem is magnified by the current trend in industry to subcontract design and maintenance decisions to contractors. These contractors benefit from the decisions in the short term only, through reduced risk and costs and increased profits, therefore they have no incentive to make the decisions for the long-term benefit of the owner/operator.

In none of the decisions evaluated here, was a formal identification of stakeholders and decision makers carried out. For some decisions, a third party was asked for advice, or offered advice unasked, but overall the decision maker made the decision unaided. For example in the first project, the decision to base the design on best estimates of temperature involved the operator, the design consultant and the installation contractor as stakeholders. The operator had to pay for the data retrieval, the design consultant had to justify the importance of the data to a successful pipeline design and the installation contractor had to carry the operational risk for the first two years. However, the operator made the final decision influenced mostly by their own preferences, with minimal input from the others. In the decision to change the pipeline route to pass through sand waves the stakeholders were the operator, APA and the installation contractor. APA made a recommendation at the conceptual design stage, however, the installation contractor made the final decision based on his own requirements without consulting APA.

In the second project, the installation contractor made the selection of the pipeline wall thickness without seeking advice from APA except to check the selected wall thickness met the design code. The decision to trench the pipeline and bury with rock was made under significant consultation from APA; however, it was so dependent on the decision

already made concerning the pipeline wall thickness, that there was only one feasible alternative. This was also the case for the decision to use a flame sprayed aluminium cooling spool to lower the fluid temperature after it was insulated by the rock cover and trenching. If the pipeline had not needed to be trenched, it would not have needed a cooling spool, therefore, the consideration and evaluation of all stakeholder influences and preferences could have stopped the contractor from installing an inoperable pipeline just because of the low installation costs.

In the third project, due to the conceptual nature of the work, there was more opportunity to identify and consult the different stakeholders. For example, the very first decision, to introduce an expansion loop into the export system was the whole purpose of the conceptual study and this therefore involved consultation with technical and commercial personnel within the operator and current and prospective third party operators. Prospective suppliers, contractors, consultants and environmental groups were also consulted through the conceptual design.

Within the more fundamental conceptual design decisions, stakeholders were considered more, but not always consulted. For example, in selecting the proposed pipeline expansion loop diameter, the different parties considered included the operator (who made the final decision), the design consultant (APA who advised the best option) the third party operators (who needed the increased capacity) and the installation contractors (who would have to install the expansion loop). However, the only stakeholders with an input at this stage were the operator and APA. Similarly, in the selection of best pipeline expansion loop configuration and in the decision to select a protection design for the expansion loop, the stakeholders considered included the operator, third party operators, installation contractors, materials and equipment suppliers, design consultants, regulatory and environmental bodies. However, these groups were not consulted.

The project management decisions were also made without clear consideration of the stakeholders. In the first two projects, the decision to award an EPIC contract to carry out the work was probably the most significant decision in that it handed all the decision-making power and the short term risk to the installation contractor, but kept the responsibility for long-term risk in house. In making the decision of who to award the EPIC contract to, the operator is not aware of the design preferences of the installation contractors and therefore cannot knowledgeably influence the future design and operation of the pipeline from that point forward.

10.3.3 Identify viable alternatives

The decision alternatives are the available courses of action between which the decision group must choose. 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. However, it is common for the real problem in decision-making to stem from a failure to produce sufficient feasible alternatives.

Evaluating the real life decisions made in APA has revealed the problems that arise when an assessment of the alternatives is not carried out. It is almost guaranteed that sub-optimal decisions will result. One or two of the design problems even involved some form of brainstorming to try to identify more design alternatives. However, even experience is not always an aid in these decisions. It can blinker the decision maker to only consider what has been experienced before (even if the situation is different), and act as a hindrance to innovation and creativity.

In the first project, the decision to base the design on best estimates of temperature considered two main alternatives. Either to issue the design consultant with process data from neighbouring fields which could be similar to the conditions in the field in question or to fund the retrieval of data specific to this field. In addition to this, other "half way" alternatives could have been considered, such as just gathering data on the most important design variables. Similarly, in the decision to change the pipeline route to pass through sand waves only two viable alternatives were considered: to route the pipeline through or around the region of sand waves. There were, however a number of sub-options that could also be included in these alternatives. For example, if routing the pipeline through the sand waves, the installation contractor could choose to pre-sweep the area to remove the sand waves, before laying the pipeline. They could trench the pipeline, either in advance of, or after, laying the pipeline. They could also backfill the trench naturally, mechanically or with rock.

In the second project, the decision to select the pipeline wall thickness involved the contractor only identifying the minimum wall thickness allowed within the pressure containment design criterion. The contractor did not consider the possibility of leaving the pipe on the seabed and so did not consider the thicker, more robust walled pipe. Consequently, in the decision to trench the pipeline and bury it with rock, the operator was fixed into a single solution. If the operator had awarded the contract to a different installation contractor, then the options would have included a concrete coated untrenched pipeline and an uncoated trenched pipeline. However, the installation contractor selected could only choose between trenching the uncoated pipeline or not. Once the untrenched pipeline was proved unsafe, it had to be trenched whatever the consequences. Finally, the decision to use a FSA spool piece to cool the pipe did address a number of alternatives through brainstorming and a pros/cons assessment. However, according to Interviewee 4, "*the different options mainly involved different coatings, the spool piece configuration did not change.*" These options were then limited further, as interviewee 3 said, "*the contractor insisted on having a first pass at the report and deleted the options they did not want*"

In the third project, because of its conceptual nature, more effort was put into identifying all the alternatives available to ensure the best decision was made. As Interviewee 6 said concerning the decision to select of the proposed pipeline expansion loop diameter, "*we looked at the effect of different diameter options, because they gave different back pressures at inlet. If you took that back-pressure as fixed, then the different diameters would give different capacities for the system.*" In addition, in the decision to select the best pipeline expansion loop configuration, as many design

alternatives as possible were generated to ensure the best design decisions were made. As Interviewee 7 said, "*we brainstormed all possible options in terms of piping layout, numbers of valves, etc. This was to get the best economic functional solution for the operator, during the project phase and over the pipeline life. We looked at about 14 options including drawing schematics to help evaluation.*" A very similar approach was also adopted in the decision to select a protection design for the expansion loop. Significant effort was put into generating all the design alternatives ensure the best design decision. As Interviewee 7 said, "*we brainstormed many different protection solutions and drew them up. These included standard steel subsea structures, square boxes with piles, raking sides, roofs to provide over-trawlability. We looked at non-symmetrical systems with different angles. We looked at plate/cone type structures, truncated cones and a half sphere. We also looked at concrete structures and a composite, GRP structure with a steel frame. It had to be piled, because a gravity structure wouldn't have worked for these trawl boards.*"

Despite all the detailed engineering assessment of each design decision, there was doubt raised over the rationality of the decision to introduce an expansion loop into the export system at all. Additional alternative solutions to the problem on insufficient capacity were not seen to have been considered. As Interviewee 8 said, "*I don't know to what extent they ever considered the alternative options for getting more gas through the system. For example one might have expected uprating the operating pressure to be fairly simple.*"

This problem of failing to identify all viable alternatives is even more pronounced in the project management decisions due to the more evolutionary manner in which these decisions are made. For example, in the first and second projects, the decision to subcontract the project, as an EPIC contract was restricted both in terms of the types of designs that were invited for tender and in the choice of preferred contract strategy. In the case of the first project, the operator had to be persuaded by APA to consider concrete coated pipe as well as reeled pipe, to allow a rational comparison of all available options to be made. In the case of the second project, the operator asked for bids for an untrenched pipeline and therefore did not carry out a thorough comparison of the trenching and non-trenching options. For both projects, other contracting options were also available, such as contracting individual tasks to different companies, to ensure the right people influenced the important issues.

Project management decisions are also constrained by circumstance, for example in the first project, the decision to select the project manager for APA's engineering work was severely constrained by the availability of suitable staff at the time of the decision. In the third project, the decision to withhold project staff from the integrated project team was also constrained by the availability of staff to be relocated away from the home office. This was magnified by the fact that the client was only willing to reimburse staff for the time worked on the project, which was not full time and they were not willing to reimburse relocation expenses. The cost implication of agreeing to such a strategy was therefore an important factor.

10.3.4 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 (e.g. considering the cost of repair and the risk of failure resulting in death or injury) or subjective (considering environmental damage and company image).

The formulation of decision objectives supports the decision process by forcing the decision group to think about the requirements for an acceptable solution and stimulating interest by providing a feeling of accomplishment. It also serves as a reference against which possible solutions can be measured and provides consensus on what is trying to be achieved.

Analysis of real life decisions identified that without the support of the decision process, the decision criteria tend to be short-term risks and costs. They are short-term evaluations because it is very difficult to quantify these consequences in the longer term, without any decision support, especially since the uncertainties increase with time. Only risk and costs are considered because they are the easiest to quantify without an understanding of multi-criteria methods. However, such a limitation on decision criteria can result in a sub-optimal decision with extensive consequences beyond costs, such as environmental, social or political, which were not identified in the decision.

In the first project, the decision to base the design on best estimates of temperature should have been based on the cost-benefit of each alternative. However the costs of the two options were straight forward to obtain, but the risks associated with basing the design on either alternative were not so easy to quantify.

The installation contractor based the decision to change the pipeline route to pass through sand waves on minimising steel costs and initial installation time and investing the savings in any necessary remedial measures. As interviewee 1 said, "*The contractor managed to persuade the operator to focus their money on the problem rather than spending extra money trying to avoid the problem because they would have the problem anyway.*" These criteria were different to those adopted by APA in the original decision As interviewee 3 said, "*APA based their decision on the fact that sand waves move, so what is mitigated now may not need mitigation in 2 years time. The sand waves won't be where they were, but they might be somewhere else and need mitigation of spanning or buckling there.*" Also as interviewee 2 said, "*We made the original decision assuming that it would be cheaper to lay the pipeline around the sand waves than to pay for the mitigation of laying it through them. However we did not have any accurate costs, so it was not a well informed decision.*"

In the second project, the contractor based the selection of the pipeline wall thickness on minimising steel cost and hence wall thickness. This was based on the contractor's best interest (who had bid for the work based on minimum cost, in order to sand the best chance of winning it), not in the operator's best interest. This was highlighted further

when it was later proven necessary to trench the pipeline and bury it with rock. This later decision was based on analysis, which according to Interviewee 5, "*was to determine for the whole life cycle, whether the proposed pipeline would be able to withstand the pipe wall damage sustained from interaction with trawl gears.*" Interviewee 4 said, "*the decision was influenced by safety to some extent due to the trawl exclusion zone around any manned installations. However, any problem would have happened in an unmanned part of the ocean. There is an associated risk to fishing vessels, although a fishing vessel is unlikely to hook onto a pipeline of that size, but a subsequent release could be a problem. There was an environmental issue, although the operator's acceptance criteria of that were unknown. The criterion was asset protection, which is fundamentally financial.*" In the end, the decision was financial. Having met the basic code requirement the decision was between minimising the height of cover and the cost of installation.

When it came to the decision to use a cooling spool to cool the pipe, the decision objective was still primarily minimising the contractor's cost. Interviewee 3 said, "*Operability did not affect the design at all, it was only once the design was complete that we had to show that it would work.*" This decision was CAPEX driven, which is typical for installation contractors, who have no interest in operational costs, except in terms of fulfilling the 2 year warranty period following installation, as part of the EPIC fixed price contract. This is expected based on the current contractual arrangements in the industry. However, according to modern management theory, as part of the operator's value chain, the installation contractor plays a very significant role in ensuring the future success of the project. Without understanding the long-term consequences of the decision and without incentive from the operator to consider the design issues in such a manner, the decision to use a cooling spool resulted in major operational problems. The cost of these operational problems was not significant when compared against the cost savings of the new pipeline, but they unnecessarily reduced the pipeline operating profits, which may in turn restrict future opportunities.

In the third project, despite the decisions being considered at a conceptual level, there was surprisingly little consideration of the decision criteria. For example, in the decision to introduce an expansion loop into the export system interviewee 8 said, "*I was never aware of any criteria being used to help decide the best option.*" The decision was more in terms of installing an expansion loop or not. Even in the decision to select the proposed pipeline expansion loop diameter, as interviewee 6 said, "*The main trade-off was in capacity versus diameter (long term revenue versus short-term costs).*" Similarly in the decision to select the best pipeline expansion loop configuration, the predominant decision criterion was financial with minimal consideration of other factors. Interviewee 7 explained, "*a matrix was written for pros and cons, relative costs and functionality for each. Because of that, we developed a simple sort of scoring system, based on money. The pros and cons considered were mainly economic such as the price of each type of valve, the cost of shutting down the line for future tie-in and the cost of shutting the line down for pigging. Safety was taken for granted.*" Again, in the decision to select a protection design for the expansion loop,

the main decision criterion was the cost of manufacturing and installing each design. As Interviewee 7 said, "*We had to ensure functionality for inspections and tie-ins, but then it was based on cost and what the contractor wanted to install. The contractor wanted to maximise their vessel utilisation and minimise the structure weight.*"

Even in the project management decisions, the decision criteria were not comprehensive or clearly identified. Often they were more significantly influenced by constraints than by positive criteria. For example, in the first project, the decision to select the project manager for APA's engineering work should have been based on identifying the project manager with the best track record for communication and good client relationships, for budget and schedule control and for an ability to view the bigger picture. However, the decision was constrained by the availability of suitably qualified staff at the time. A similar problem was the basis for the decision in the third project to withhold project staff from the integrated project team. The main decision criterion was the constraint on the team members' availability for full time project commitment.

In the first and second projects, the decision to subcontract the work as an EPIC contract was based on the operator's desire to minimise capital expenditure and risk. However using an EPIC contract left the operators no control over the design. The operators chose EPIC contracts to avoid taking the risk themselves and to pay someone else to carry the risk. Once the work was awarded to the installation contractors the decision maker changed from the operator to the contractor, this meant that the design objectives changed from minimising cost and risk for the operator to minimising cost and risk and maximising revenue for the contractor. The focus became very biased towards short-term issues.

10.3.5 Structural analysis

In many decisions, it is necessary to break the main decision into smaller parts (this is the benefit of decision analysis). Depending on the decision problem this can mean subdividing the decision on different bases, depending on which most helps to solve the problem. There could be a series of decisions to be made over time, where each sub-decision requires a follow-up action. Alternatively, the selection of one alternative could open up a whole series of other alternatives or events. A decision matrix, a decision tree or an influence diagram can represent these.

The review carried out in this case study revealed how rarely such powerful tools are applied in practice despite the benefits and clarity it can bring. There is no example from experience to show the use of these techniques without prompting from the proposed decision process. However, there is evidence in nearly all of the examples, of the decisions not being clearly formulated or communicated and therefore resulting in sub-optimal decisions.

Several of the examples showed that the timing of decisions was not used to the best advantage and decisions were made before all the information was available. In some cases, this occurred even in the knowledge that the information would become available later. However, the schedule required that the decision must be made before the

information was available. The consequence of this was a number of sub-optimal decisions. Therefore, although it appears initially to be a very small consideration within the whole decision process, accounting for the timing of the decisions can play a very significant role in determining how well the decision is made.

There were also a number of cases where the decision was made without using all the available information or even without identifying all the information that was available. This means that, in hindsight, the decision appears to be illogical and certainly sub-optimal. It is clear, therefore, how important it is to base a decision on the maximum available information, and then to evaluate the cost benefit of obtaining further information if necessary.

One of the key examples of this was in the first project in the decision to base the design on best estimates of temperature. This whole decision concerned the availability of information and the timing of the decision. The risks of design failure could not be easily quantified, but a subjective evaluation could have helped this decision. A risk-based decision tree could have been constructed to show the "expected cost" of each alternative. This would have included the cost of data collection, the probability of an unsuccessful design based on the available data and the cost of remedying the design or operating below the original design. This may have shown that decision was dominated by the cost of delay to first revenue and therefore prefer making a decision based on sub-optimal data, or it could have highlighted an unbearable risk of failure without the data. As interviewee 2 said, "*the design sensitivity to these parameters should have been evaluated.*" This would have allowed the best decision to be made if there was sub-optimal data.

The decision to change the pipeline route to pass through sand waves was also based on very little data and many assumptions and uncertainties. A formal consequence evaluation of each alternative would have put this decision's significance into perspective, which would also have helped identify the key information. However, from the contractor's viewpoint, the decision was based on their own financial risk, not on the overall project risk, therefore from their perspective they made the best decision. In other words, the contractor succeeded in minimising his own costs while the operator took on all the risk.

In the second project, the contractor's decision criteria in the decision to select the pipeline wall thickness were a subset of the full decision criteria that the stakeholders would have wanted to be applied. Therefore, the contractor did not worry that the pipeline could not remain untrenched since he excluded it as a risk by passing it back to the operator. Therefore, the consequences of selecting such a thin wall thickness were not considered from the operator's perspective. The contractor had considered the potential of upheaval buckling problems due to trenching the line (required by the thin wall thickness), but had underestimated the cost of rock required and the insulation consequences of installing the rock cover. However, because the contractor had wanted to win the work, they had minimised their own costs and passed the risk back to the operator. A different choice by the operator at contract award could have changed

everything. However, the decision to award the contract and allow thin walled pipe meant that the decision to trench the pipeline and bury it with rock then had to follow. This decision made by the operator, therefore, was not structured, because although the consequences of not trenching the pipeline were identified and fully evaluated, the consequences of trenching it were not. The mitigation against the consequences of not trenching the pipeline was not considered, so the overall best option could not be identified. However, at the conceptual stage, the operator had collected all the information they had on the existing line, how it worked, on the fishing activities, the seabed soils etc. They even carried out impact tests on concrete coated pipe, but not uncoated pipe. The contractor believed they had sufficient information to prove the pipeline had to be trenched. This unstructured decision-making by the operator continued through to the decision to use a cooling spool. The consequences of sufficiently cooling the pipe contents to mitigate against the upheaval buckling were not considered. The consequences of insufficient information in the cooling spool design can be seen in the subsequent operational problems now experienced by the operator.

In the third project the conceptual evaluation of the design meant that more time could be spent evaluating the decisions and gathering necessary information. For example, in the decision to introduce an expansion loop into the export system interviewee 2 said that, "*they had to go to their partners with a realistic detailed costing of the proposed system. That meant that they had to involve an installation contractor and give a commitment to them to do it at that price*". However, interviewee 8 felt that no structural analysis was carried out of this decision but that "*they made the decision at a very high, simplistic level.*"

In the decision to select the proposed pipeline expansion loop diameter, interviewee 6 said, "*the effect of different diameter options was considered, also later on, the risk of frost heave was raised. That could have had further risks associated with it. It could have been a much lower temperature than we had predicted, or it could have been higher and then we would have had no problems. There was quite a lot of money riding on that, because they were talking about installing a heater. If we had predicted low temperatures and they hadn't occurred then they would have spent two million pounds on something they did not use.*" The information needed to support this decision was identified. However, as Interviewee 6 said, "*at the design stage, the project manager presses us to get results out to the client, even if we haven't got the right information. We can do the analysis, but the results are uncertain. We have to make assumptions.*"

In the decision to select the best pipeline expansion loop configuration and in the decision to select a protection design for the expansion loop significant effort was put into gathering enough information to rationally evaluate each alternative. This meant the decision consequences were well understood.

In the project management decisions, there also seemed to be little consideration of the information required to support the decisions, the consequences of those decisions or methods for controlling those consequences, such as in the first project, in the decision to select the project manager for APA's engineering work. This was also the case in the

third project in the decision to withhold project staff from the integrated project team. These decisions were necessarily more influenced by the strong external constraints of staff availability than an assessment of decision consequences.

In the first and second project decisions to subcontract the work as an EPIC contract, there was some consideration of available information presented in the proposal documents issued by each potential contractor. However, structural analysis would have identified the consequences of the decision and may have identified the contractor's own agenda for the project.

10.3.6 Uncertainty and probabilistic analysis

Since uncertainty is such a critical element of many decisions that are faced, it is necessary to consider this in the decision modelling process. This, however, is one of the most difficult stages of the decision process.

The decisions evaluated as part of this case study showed that an evaluation of all possible outcomes does not always take place as a number of decisions have resulted in outcomes that were totally unexpected at the design stage. These are obviously unwanted and can be very expensive especially for the long-term operator of the asset.

For example, in the first project, the decision to base the design on best estimates of temperature involved significant uncertainties that should have been accounted for. No attempt was made to evaluate the likelihood of the estimated data being incorrect and having an adverse effect on the design's operability.

The interviews carried out also identified that the decision-maker ignored some risks, which were not of low probability or of low consequence. The decision-maker did not want to acknowledge these risks, to save the problem of mitigating against them. However, problems arose later when some "unexpected" outcomes occurred, creating additional costs for the operator to cover. These should have been identified, evaluated at the time of the decision to allow the operator to understand fully the implications of the risk to mitigate against them.

For example in the decision to change the pipeline route to pass through sand waves, the installation contractor was aware of the consequential risks of upheaval buckling, but passed these risks back to the operator. However, the operator made no consideration of how to quantify or control them. As interviewee 1 said, "*they came back to us with the out of straightness profile, which had a lot of noise on it from the way that they had measured it. The measurements were taken sporadically almost as if they did not care about the data quality, because the installation contractor had allowed for risk in the analysis. Ultimately, it was their risk to some extent as they were trying to impress the client by showing they had made the right decision. However, the better the data quality, the better the analysis quality and maybe the savings that they could have made. But a large amount of required mitigation was due to the noise level.*"

Similarly, in the second project, in the decision to select the pipeline wall thickness, the contractor did not care that the pipeline might not be able to remain on the seabed, since they had already passed the risk back to the operator. This led to the decision to trench

the pipeline and bury it with rock, which was based on a detailed risk assessment by APA of the pipeline based on the pipeline being dented by fishing gear with a very smooth dent. However, as interviewee 5 said, "*there was no formal risk quantification just an assessment based on expert opinion and available information.*" Interviewee 3 continued, "*the main risk considered for the non-trenched case was the loss of containment due to pipeline fatigue and denting. There was limited data on the fatigue life of dents in welds and of kinked dents. The likelihood of a leak was calculated as 1/100.*" Interviewee 5 said, "*APA were also at risk, because if we had said that it could be installed untrenched when it could not, then the pipeline would have failed prematurely. We would have been sued by Contractor 2, and our reputation would have suffered.*" This then led to the decision to introduce the cooling spool, to minimise contractor's costs, which resulted in a practically inoperable pipeline. The risks of the cooling spool not working were not considered. Interviewee 4 thought, "*the risks to the contractor weren't ignored, but it was assumed that they could be negated in the design process.*" The problem was that different stakeholders were carrying different risks. The installation contractor was responsible for the installation costs, and therefore had to cover the cost of rock and/or the cooling spool. The operator carried the operational risks, but they were not under his control. If a risk evaluation had been made of the decision, on behalf of all stakeholders, even when the decision to trench had been made, these consequences may have been foreseen and the optimal decision may have been for the operator to pay for the extra rock costs if it was going to improve the design. Instead, the operator now has a very expensive long-term problem if the pipeline is to remain in use.

Even in the third, conceptual design project, the decision to introduce an expansion loop into the export system did not evaluate the risks of the expansion spool not fulfilling its design objective or of it not being the best option available.

However, in the design level decisions to select the proposed pipeline expansion loop diameter and the best pipeline expansion loop configuration a number of risks and uncertainties were identified. As Interviewee 6 said, "*there was a risk of capacity being different to that predicted. We had to base the design on a given flow rate and pressure drop, but you don't know if that is wrong until you can validate the model against the pipeline system. The risk of frost heave was taken seriously because of the serious consequences of pipeline failure.*" The probabilities of these hazards were also assessed according to interviewee 8, through a number of coarse HAZOP exercises.

However, when it came to the decision to select a protection design for the expansion loop, the risks associated with each option were not identified or evaluated. This should have been a significant part of the decision due to the different risks involved in the installation of each design. In addition, each design would have had a different effectiveness in terms of protecting the pipeline from trawl gear impact.

In the project management decisions, there was also no consideration of the uncertainties and risks involved. For example in the first project's decision to select the project manager for APA's engineering work, the uncertainty in the success of the

project under the selected manger may have been considered. These may not have been avoidable (due to the lack of alternatives), however they could have been controlled, through monitoring and feedback, to ensure the project was a success according to its original objectives. Similarly in the third project's decision to withhold project staff from the integrated project team, the consequences of being separate to the integrated project team were not investigated or understood.

Finally, in the first two projects' decisions to subcontract the work as an EPIC contract, the operator did not assess the risks involved. Hindsight showed that no safeguards were in place to control the risks of the contractor ignoring the operators design preferences.

10.3.7 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; one is the decision-makers' preference between the decision criteria, i.e. the criteria weightings. The other type of preference is the decision maker's tolerance to the decision consequences, i.e. the value/utility of the consequences.

Evaluation of the real life decisions in this case study revealed that the main decision criteria were identified by the decision maker in accordance with their own preferences, without consultation with other, often important, stakeholders such as the operator. Frequently, it was also noted that some decision criteria, even if they were important, were ignored if they were difficult to quantify.

Furthermore, there was no evidence of any quantification of preferences. However, there was evidence of deliberate preferences being introduced by the decision maker, for example preferences for minimising short term costs rather than long term costs and minimising short term risks rather than long term risks.

For example, in the first project, in the decision to base the design on best estimates of temperature, APA was keen to have the best possible data to ensure the most effective design. However, according to interviewee 1, "*the operator wanted to proceed the work prior to having definite information available but the installation contractor refused to carry the risk associated with this decision and passed it back to the operator.*" As mentioned before, a sensitivity analysis of the important parameters and their influence on the overall design would have helped make the best decision under such constrained circumstances.

In the decision to change the pipeline route to pass through sand waves, APA's preference had already been made clear at the conceptual design stage when they recommended avoiding the sand waves. According to interviewee 2, "*the risks assessed very subjectively based on experience. We made the decision to avoid the sand waves assuming it was the lowest cost option. I do not think the operator had any preference at that stage, and were relying on our recommendation. However, the contractor disagreed with our assumptions.*" In the end the decision was based on the installation

contractor's preference with no account made of either the design consultant's or the operator's preferences.

In the second project, the decision to select the pipeline wall thickness was based on the contractor's preference to minimise their own cost and maximise their revenue. They wanted to minimise their own risk, both now and through later design decisions. As the design progressed to the decision to trench the pipeline and bury it with rock, these preferences remained dominant with no account of any other stakeholders' preferences. Finally, in the decision to use a cooling spool, the contractors preference was clear, as interviewee 3 said, "*when the cooling spool was being designed everyone knew that the contractor wanted a cooling spool to be as long as possible to reduce the temperatures to minimise rock costs.*" However, the operator's preferences were not accounted for.

Even in the third project, the preferences of other stakeholders were not accounted for. In the decision to introduce an expansion loop into the export system, the only real decision maker was the operator. As Interviewee 2 said, "*the oil companies tend to keep a lot of information very close to their chests. To them, although they are technically under-resourced, knowledge is power. They do not tell you the full story because they want to be able to influence the outcome. Maybe if you worked closely with them for years, you might be able to build a proper relationship where you can understand their objectives, that would be much better.*"

The decision to select the proposed pipeline expansion loop diameter was significantly influenced by the operator's preferences (especially the commercial department). As Interviewee 6 said, "*the operator knows the revenues, they know where they're going to sell it, and they know the lay schedules, so they make the decision, we just made some design recommendations. There is a lot of politics involved in the decision-making. The contractors want to be involved at every stage to look more important. The project managers are more concerned with hitting their project milestone, than with making sure the best possible design decision is made. The project managers can be completely schedule driven and not worry about the consequences of making ill-informed design decisions.*"

According to Interviewee 7, the decision to select the best pipeline expansion loop configuration involved a number of preferences and biases, which were well accounted for in the design process. "*The decision-making was an evolutionary process involving the team at all stages. An external peer review was also carried out to demonstrate the decision process and to get feedback.*"

Finally, the decision to select a protection design for the expansion loop was heavily influenced by the installation contractor's preferences. As Interviewee 7 said, "*the installation contractor wanted to minimise the component's size and weight to be able to use a smaller installation vessel. They could do it more cheaply, with a higher margin, with their small vessel instead of hiring a bigger vessel.*"

A similar lack of consultation seemed to take place in the project management decisions such as the first project's decision to select the project manager for APA's engineering

work and the third project's decision to withhold project staff from the integrated project team. Different stakeholders had different preferences concerning these decisions who, if they had been consulted may have had more understanding and ownership of the final decision, whether they agreed with it or not.

In the first two projects' decisions to subcontract the work as an EPIC contract, the operator made himself very vulnerable by not identifying the biases and preferences of the contractors that they were considering.

10.3.8 Selection of "best" alternative

Once the attributes have been evaluated, the best alternative needs to be identified in the most rational manner.

The decisions, which were investigated here, were often based more on preferences and perceptions of cost and risk than any clear optimisation of calculated values despite carrying out detailed calculations in some cases. Therefore, although the best decision may have been considered to be made at the time, these were often based on non-ideal, or even biased criteria, which meant that the best decision overall, for all stakeholders, was not always made. It can, therefore, be seen to be very important to continue the logic of the decision-making process right to the conclusion of the decision and to ensure the best option is selected based on the specified criteria.

For example, in hindsight it is obvious that in the first project's decision to base the design on best estimates of temperature the best decision was not made. The operator decided not to fund the retrieval of local information but to carry the risk of basing the design on estimated data. As interviewee 1 explained, "*at the end of the job, when we were doing upheaval buckling analysis, the actual flowing temperatures were above what our design temperatures were.*" This meant that increased mitigation measures were required at additional expense.

It is very difficult to know whether the installation contractor feels that the right decision was made changing the pipeline route to pass through sand waves. It is also difficult to know yet whether the right decision was made for the operator or not. That will become more apparent if the transient seabed begins to cause spanning and buckling problems later.

In the second project, it is very clear that the best choice of the pipeline wall thickness was not made for the operator. The contractor chose a pipe wall thickness that based on the risk analysis was found to be unsuitable to remain on the seabed. The decision to trench the pipeline earned the contractor additional fees for trenching the pipeline, so the contractor finished the project financially very well. However, the pipeline was then found to be over insulated, resulting in the need to reduce temperature. However, as interviewee 4 said, "*APA knew during the design process that the cooling spool wasn't a good design, it works, but not very well.*" The resulting operational problems show a very poor train of decisions for the operator, but the contractor minimised their costs and were paid extra for trenching the pipeline.

Interviewee 4 felt, "*the contractor probably wouldn't do it differently if they did it again, because they did very well out of the job. They believe the cooling spool was a robust option, because their decision was not OPEX based. A reasonable solution for a reasonable cost, in the period allowed, is a success. However, the operator would do it differently, because they know what they have ended up with. It wasn't a conceptually difficult design, but they've ended up with an expensive solution.*"

It is very difficult to judge whether the best decisions were made in the third project, as it was not carried through to completion. However, it would be very difficult to prove that decision to introduce an expansion loop into the export system was the best with no other alternatives considered and no results on which to evaluate it. The selection of the proposed pipeline expansion loop diameter was at least carried out rationally and thoroughly so it stands a good chance of being successful had the project moved forward to completion. The same can be said for the selection of the best pipeline expansion loop configuration. As Interviewee 7 said, "*The option we chose wasn't the cheapest but it had increased functionality for the field life, so it was a good trade-off against price.*" Finally, the decision to selection a protection design for the expansion loop was also considered workable and had been made rationally. As Interviewee 7 said, "*We would have taken the composite structure solution further had the project gone on to the next phase. Any of the options would have been more than adequate for the field life.*"

The project management decisions are very difficult to evaluate in this way because they involve much softer issues and become quite personal. However, it is believed that although the selection of the project manager for APA's engineering work on the first project was the only decision possible it did result in a number of problems that indicated that it was not best. Additional project controls could have helped stop this problem from escalating in the way that it did. A similar conclusion can be drawn for the decision to withhold project staff from the integrated project team in the third project. Again, this decision was made because no other suitable alternative could be identified, however, as interviewee 7 said, "*We had much less input to the team. The main lesson is that if you have the chance to be a part of an integrated project team then you should take the best possible advantage of it.*"

It is difficult to determine whether the best contractor selection decisions were made. However, the projects did result in design and operational problems that may have been avoided had the operator had more control on the design decisions.

10.4 Conclusions

This case study has reviewed some real life risk-based decisions made in conceptual and preliminary engineering design at APA. APA's senior engineers and managers identified previous projects where the main design decision basis was known.

This review has revealed that APA's clients make many major conceptual design decisions before APA is commissioned with the task of completing the design. These decisions and the contracting strategy then restrict the way that APA can complete the

designs, which can result in sub-optimal solutions. This causes problems for the client or the operator and reflects badly on APA.

The main decisions that have been evaluated can be grouped together into project management issues and design issues. The conclusions for these two areas are quite different and therefore will be addressed separately.

10.4.1 Project management issues

The following decisions investigated were dominated by project management issues:

1. To select the project manager for APA's engineering work.
2. The decision by the client to subcontract the work via a contractor.
3. The decision to award the work as an EPIC contract to Contractor 2
4. To introduce an expansion loop into the export system.
5. To withhold project staff from the integrated project team.
6. To base the design on best estimates of temperatures.
7. To change the pipeline route to pass through the sand waves.
8. The decision to trench the pipeline.

The first five decisions within the project management group are clearly project management issues, however it could be perceived that the sixth, seventh and eighth decisions are more related to design issues as they are the selection design input variables. Project management issues however, motivated these decisions.

Analysis of these decisions has shown that the problem is not always correctly identified or understood which can cause significant problems both through the ensuing decision-making and in the implementation of the decision, which either becomes sub-optimal, or the key criteria are not controlled. For example in decision 1, the problem was not to select a project manager but to ensure the project was controlled and executed in the best way. In decisions 2 and 3, the problem was how the operator should control cost and risk, but by passing over all responsibility, neither was controlled. In decision 4, the problem was not to introduce an expansion loop, but how best to increase capacity. In decision 5, the problem was not how to maximise the project margin with minimum disruption to other projects but how to best contribute to the project, at maximum margin and minimum disruption to other projects. The decisions 6, 7 and 8 were, however more fully identified due to the design basis of the decision-making.

Stakeholders were an issue (both individual and corporate) in all of these decisions. Different stakeholders were interested in different decision outcomes. However, the stakeholders' views were not taken into account. In decision 1, some viewpoints were assumed (wrongly), while others were not even considered. In decision 2, the decision-maker seemed unaware of the stakeholders trying to influence the decision to benefit themselves. In decision 3 at least two groups of stakeholders were also significantly

influencing the decision with biased information. In decision 4 too, A large number of stakeholders both internal to the operator and external third party organisations were interested in and some even influencing the decision. In decisions 5 and 6, a large number of stakeholders apart from the decision-maker were affected, but none of their views were taken into account. In decision 7, the stakeholders with the most knowledge and experience were not consulted at all and the decision was biased by the decision-maker's preferences. Finally, in decision 8, the operator was the long-term stakeholder but due to the contract they had set up, they excluded themselves from being part of the decision-making. An identification of the stakeholder issues in any of these decisions would have helped the decision-makers to be more logical in their decision-making.

In decision 1 there were no other suitable candidates available, however the options should have included controlling the risks. For decisions 2 and 3, the operator did not appear to fully identify and consider all the alternatives available, both in terms of contractual options and in terms of limiting the design options, however it is quite possible that these contracts were dictated by company policy. It was felt by those interviewed that very little consideration was made in decision 4 of the alternative solutions available in addition to the introduction of an expansion loop. In decisions 5, 6, 7, and 8 only two main alternatives were identified. Variations and sub-options on these main alternatives should have been developed. The lack of alternatives for most of these decisions certainly influenced the decision made. Most of these decisions could have been improved upon had more attention been paid to generating as many viable options as possible.

Decision 1 was significantly restricted by the lack of available alternatives, however the decision criteria could have been more clearly identified to allow control of the achievement. Decisions 2 and 3 were purely based on minimising capital cost and risk to the operator. However, once the work had been awarded to the installation contractor the decision maker changed and so the design objectives changed from minimising the cost and the risk for the operator to minimising the cost and risk and maximising the revenue for the contractor. The issues became very short term in focus. In decision 4, very little consideration was made of what the criteria the decision should be based on. Decision 5 was also made on very short-term issues, such as the current staff availability rather than the long-term benefit to the project and the company. Decision 6 was also made in terms of cost only, the benefit of each option was not considered. Decision 7 was based on minimising known capital costs and using any savings to offset unknown remedial costs. However, because these were unknown and no attempt was made to quantify them, this decision became less rational. Decision 8 was also made on purely financial grounds in terms of minimising the rock cover height and the installation cost. Although most of these decisions were made on purely financial grounds, none was affected by costs alone. Other criteria should have been considered, such as risks to other stakeholders, whole life costs, operating life and environmental impacts, to enable the best decision to have been made for all.

No structural analysis was carried out for any decision in the section. This meant that there was no formal consideration of the long-term effect of these decisions. Structural

analysis is a powerful tool for getting a "bigger picture" of the whole situation. If structural analysis had been made of the decision there may have generated some appreciation of the decision consequences and the factors influencing them could be gained. In some decisions, the decision-maker may have become aware of other stakeholders' agendas. In addition, some decisions may have been recognised as being more significant than was otherwise credited to them.

In decision 1, the only information available to support the decision-making was personal opinions and experiences, but these should have provided a warning of the likely risks, to ensure sufficient controls were put in place. In decisions 2 and 3, there was no consideration made of the information required to support the decision-making, except what was asked for in the proposal documents, but this blinkered the operators to the risks that they were exposing themselves to. In decision 4, the identification of data requirements had been carried out to some limited extent. Decision 5 did not involve any investigation or collection of support data, because the decision makers were so constrained by costs into selecting one alternative. Decisions 6 and 7 were based on very little data and many assumptions and uncertainties; however, sensitivity analysis of the main parameters would have identified the important issues to allow them to be controlled. In decision 8, significant amounts of data had been collected, but the problem the decision-maker faced was how to use the information rationally to support the decision-making. The proposed decision process would have ensured that the need for information had been taken seriously in all of these decisions, but also that the information was used in a structured manner to the best use possible.

In decision 1, the uncertainties and risks involved were identified, but there was no effort to control them. This meant that the project developed out of control, at the expense of client relationships, and profitability. In decisions 2 and 3, the operator did not assess the risks involved in awarding the EPIC contract the contractor. Therefore, no safeguards were put in place to control the risks of the contractor ignoring the operators design preference. In decision 4, there was no consideration of the risks of the alternative not fulfilling its design objective. Decision 5 was so strongly constrained by the risk of financial failure, that there was only the one option sensibly available. Decision 6 also involved a significant degree of uncertainty that should have been accounted for, but sensitivity analysis of the design parameters this could have been better understood. The installation contractor did not try to quantify the risks when they made decision 7; instead, they passed all the risk back to the operator, who also failed to consider its implications. In decision 8, the risk assessment identified uncertainties more thoroughly however, one alternative was considered in much more detail to the other. Most decisions, therefore, involved significant risks and uncertainties, which were not investigated or rationally and fairly accounted for in the decision. On the occasion that they were identified they were used in a biased manner to manipulate the decision. The risk-based decisions process would have helped identify all the risks and use them in a rational manner to support the decision-making.

In decision 1, the stakeholders' preferences were not assessed by consultation but by assumption, especially in terms of who the client would accept as project manager.

Unfortunately, the assumptions were wrong, this influenced the decision and its acceptability to the stakeholders. In decisions 2 and 3, no attempt was made whatsoever to identify or evaluate the stakeholders' biases in the decision, which left the operator exposed to the risks, which they were trying to pass over. The decision-maker of decision 4 only considered his own preferences; none of the other stakeholders was considered. In decision 5, the stakeholders other than the decision-maker could see both sides of the decision and identify which was the best. However, the decision-maker could only see the decision biased by his preferences, which meant the best decision was not made. Decisions 6, 7 and 8 were also heavily influenced by the contractor's preferences, with little recognition of anyone else's preferences, including the operator's. The problem with all of these decisions, ignoring the stakeholder preferences meant that the decision was often not best for the most important stakeholder, the operator, neither was it supported by the stakeholders who had to make it work. This results in below optimum designs. The risk-based decision process would have ensured that these issues were considered and even accounted for.

It can be seen quite clearly that none of these project management decisions, whether taken internally to APA or externally by operators or contractors, were made on an entirely rational basis. Comparison with the proposed decision process presented in Chapter 2 shows that these decisions did not always address the true problem and that they made very little recognition of stakeholder influence, no generation of viable alternatives, limited availability of information and no risk or consequence assessment. Furthermore, the decisions were made on very strong decision-maker biases. The lack of rationality in these decisions was revealed in the consequences that became clear after each decision. These consequences were made more severe by the lack of feedback and control through the implementation of the decisions; in terms of ensuring the decision objectives were met.

Therefore, it is not possible in any of these decisions to say that the best decision was definitely made. In some decisions, it is clear that the best decision was not made. Other decisions were so poorly evaluated that it is impossible to tell whether it was the right decision or not, without reanalysing the whole process. This would involve identifying all the stakeholders, alternatives and decision criteria, collecting enough information to support the decision and evaluating the risks and stakeholder preferences. Unfortunately, this is not possible so long after the decisions were made. The information and sometimes even the decision-makers are no longer available. Such a reanalysis of the decision is a form of very detailed sensitivity analysis. If such an analysis had been carried out at the time of the decision, as prompted by the risk-based decision process, there would have much more confidence in the final decision.

10.4.2 Design issues

The remaining decisions that were investigated, listed below, were found to be predominantly design issues, although the first two were driven by the fixed price contract strategy:

1. The selection of a minimum pipe wall thickness

2. The selection of a pipeline cooling method.
3. Selection of the diameter for the proposed pipeline expansion loop.
4. Selection of best pipeline expansion loop configuration.
5. Selection of a pipeline expansion loop protection design.

In all of these decisions, there would have been a number of stakeholders either influencing or influenced by the decision although in none of the decisions were they formally identified and accounted for. The only stakeholder involved in making the decision in each of these cases was the installation contractor, although advice or reassurance was sought from APA in each decision and from the operator in decisions 3 and 4. This means that the best decision was not necessarily made for the right people.

In decision 1, there was no attempt to generate enough alternatives apart from minimising the wall thickness against the design criteria, although this ensured that the contractor's goal of minimising his own costs was met. In decision 2, the options were considered very briefly in terms of the design concepts but they were assessed at a very high level and quickly discounted. In decisions 3, 4 and 5, significant effort was put into identifying all the alternatives available through brainstorming and quantitative evaluation to ensure the best decision was made. Only in these last three decisions can the stakeholders have any confidence in the decision, knowing that the option selected had to win against so many other alternatives.

In decision 1 and 2, the overall decision objective was to minimise the design's capital cost to the contractor. No attempt was made to evaluate the alternatives against whole life costs, operability, design life or safety, which are also important factors in design from the operator's perspective, but not from the contractor's perspective. In decision 3, a number of decision criteria were identified and considered; in addition, rough costs were put to each option to allow a comparison of cases. In decisions 4 and 5, the alternatives were evaluated quite rationally although the predominant criterion was still financial with minimal consideration of other factors.

Because of the limited decision criteria used by the contractor in decision 1, there was no consideration of the decision consequences; this was because the contractor had passed all risks back to the operator's account. In addition, in decision 2, no formal decision problem structuring was carried out. In neither decision did the decision-maker, who was the contractor, demonstrate any openness to the negative consequences of their decisions, as the operator carried all these. In decision 3, no formal structural analysis was carried out of the decision alternatives and possible outcomes; however, the effect of different diameter options was considered. In decision 4, the design decision consequences were fairly well evaluated and understood due to the quantitative analysis. In decision 5, there was no evaluation of each option's performance. Such an ad hoc view of evaluating the consequences of such significant design decisions does not support the decision-maker in arriving at the best decision for all stakeholders.

In decision 1, clearly there was not sufficient information on which to base the decision because if a complete mapping had been made of the decision, the risk of upheaval

buckling caused by trenching the line would have been better understood, it was identified, but qualified out against an estimated cost of rock mitigation. The consequences of not having enough information in the cooling spool design can be seen in the subsequent operational problems that the operator is experiencing now. In decision 2, some consideration was made of the information needed to make this decision as rationally as possible. However not all the information needed was available so assumptions had to be made. In decisions 3, 4 and 5 a significant amount of effort was also put into ensuring enough information was gathered to be able to rationally evaluate each alternative. This meant that a thorough comparison of each option could be made.

In decision 1, the contractor was not willing to accept the risk of the pipeline not being robust enough to remain on the seabed. Therefore, the risks of selecting a thinner wall thickness were transferred to the operator. In decision 2, there was also no evidence of the contractor considering the risks of the cooling spool not working, as these were also transferred to the operator. Although current contracting strategy does not encourage the installation contractor to be concerned with long term design consequences, this would add considerable value to the decision-making for the operator and ensure the implementation of much more successful designs. In decisions 3 and 4, significant effort was put into identifying and evaluating the risks. An attempt was also made to quantify the probabilities of these risks. However, in decision 5 there was however, no identification or evaluation of the risks associated with each option.

Decision 1 was dominated by the installation contractor's preferences to minimise their own costs and risks, as were decisions 2 and 5. In none of these decisions, were the long-term operator's preferences accounted for. This resulted in design solutions with which the operator was not necessarily happy. In decision 3, however, the decision was entirely dominated by the operator's preferences. Even so, this did not mean that the technical issues were considered rationally without bias. This is because the operator's commercial department heavily influenced the decision, with minimal input from the technical department. Decision 4 was the only decision out of this group of decisions that is described by the interviewees as being made rationally by recognising and taking into account the preferences and biases of all stakeholders.

It can be seen that decisions 1 and 2 were not made in the operator's best interest but the contractor's. If the decision analysis process had been adopted in these designs, then all stakeholder values would have been taken into account. This would have allowed consensus to be built and the decisions to be made in the best interest of all parties. In decisions 3, 4 and 5 it is not possible to determine whether the best decisions were made or not, since the project was not brought to completion. However, both decisions were evaluated in a logical and thorough manner, with detailed assessments of all the alternatives. The solutions may have changed, if more thorough risk and stakeholder preference assessments had been made as recommended in the proposed design process.

As concluded in the previous section, it is not possible to say for certain that the best decision was made in any of these decisions. In some decisions, it is clear that it was

not. Other decisions were so poorly evaluated that it is impossible to tell whether it was the right decision or not, without reanalysing the whole process. This would involve identifying all the stakeholders, alternatives and decision criteria, collecting enough information to support the decision and evaluating the risks and stakeholder preferences. Unfortunately, this is not possible so long after the decisions were made. The information and sometimes even the decision-makers are no longer available. Such a reanalysis of the decision is a form of very detailed sensitivity analysis. If such an analysis had been carried out at the time of the decision, as prompted by the risk-based decision process, then there would have much more confidence in the final decisions.

Overall, these design decisions were made under significant uncertainty and were susceptible to the decision-makers' preferences and experience, but they were made much more rationally than the project decisions. There was evidence of processes similar to the proposed decision process being applied.

At this early stage of the structure's life, the decision-maker is faced with the most significant risks, with the consequences having to be lived with for the structure's remaining life. Risk-based decision-making can help to fulfil these requirements. There are several benefits of using risk-based decision methods to support concept selection, conceptual and preliminary engineering design of new structural assets. The strengths and weaknesses of each concept can be considered fully in the design problem context. This allows for a wide number of factors to be the decision basis (and allows project as well as design issues to be accounted for). In other words, the lowest cost concept would not necessarily be selected if it had a very high risk of failing. Similarly, the opinions of a wide number of stakeholders can also be accounted for. By taking account of the uncertainties in different concepts (unknown operating environments, unknown demand of supply etc.), the best decision for the most likely combination of situations can be made while protecting against the largest loss. Finally, by introducing a final step in the proposed risk-based decision process, to include feedback, monitoring and control of the decision implementation, the risks and decision objectives can be controlled to ensure that the best decision is implemented to its fullest potential.

11 DISCUSSION

The work presented in this thesis was initiated following the identification of a potential need in the management of engineering structures. It was suggested that support in making the decisions about the management of such assets would result in a better allocation of resources and help maximise the benefits that could be obtained from the limited resources available.

Based on a review of the literature (concentrating on classical decision theory and on previous attempts to use decision-making techniques in this area), a generic decision process was proposed. This process was then applied to four real-life case studies, drawn from problems current at the time of the work. This means that the whole exercise was entirely realistic, in terms of the availability of information, the interactions and politics between the stakeholders and the deadlines for recommending solutions. A fifth case study examined how real-life unsupported decisions had been made within the sponsoring company and compared these against the proposed decision process.

Following each of the case studies, lessons were learnt concerning the usefulness and completeness of the decision process. As a consequence, the process was reviewed and improved. The final proposed risk-based decision process is now quite different to that outlined by Keeney and Raiffa [23]. The two models are compared in figure 33 below, with the enhancements shown as shaded boxes. This figure highlights where the new proposed risk-based decision process has been enhanced from Keeney and Raiffa's process. It now includes stakeholder analysis, early formulation of decision criteria and objectives, identification of preferences between decision criterion in addition to preferences between outcomes, sensitivity analysis, the opportunity for re-analysis if necessary and the monitoring and control of risks and objectives during implementation. The enhanced process provides a much more thorough evaluation and implementation of decision-making, than was considered possible at the beginning of this research.

The case studies examined varied widely in terms of when the decisions were made in the structure's life cycle as well as in the way they fitted the proposed decision process. For example, the influence of stakeholders, risk, uncertainty and the availability of supporting information varied between case studies.

Table 65, which follows the figure, compares each of the case studies in terms of the proposed decision process, and therefore allows a number of conclusions to be drawn.

The subsequent sections compare the five case studies with each stage of the proposed decision process. The first four case studies are considered separately and compared with the fifth case study, from which different lessons can be learnt.

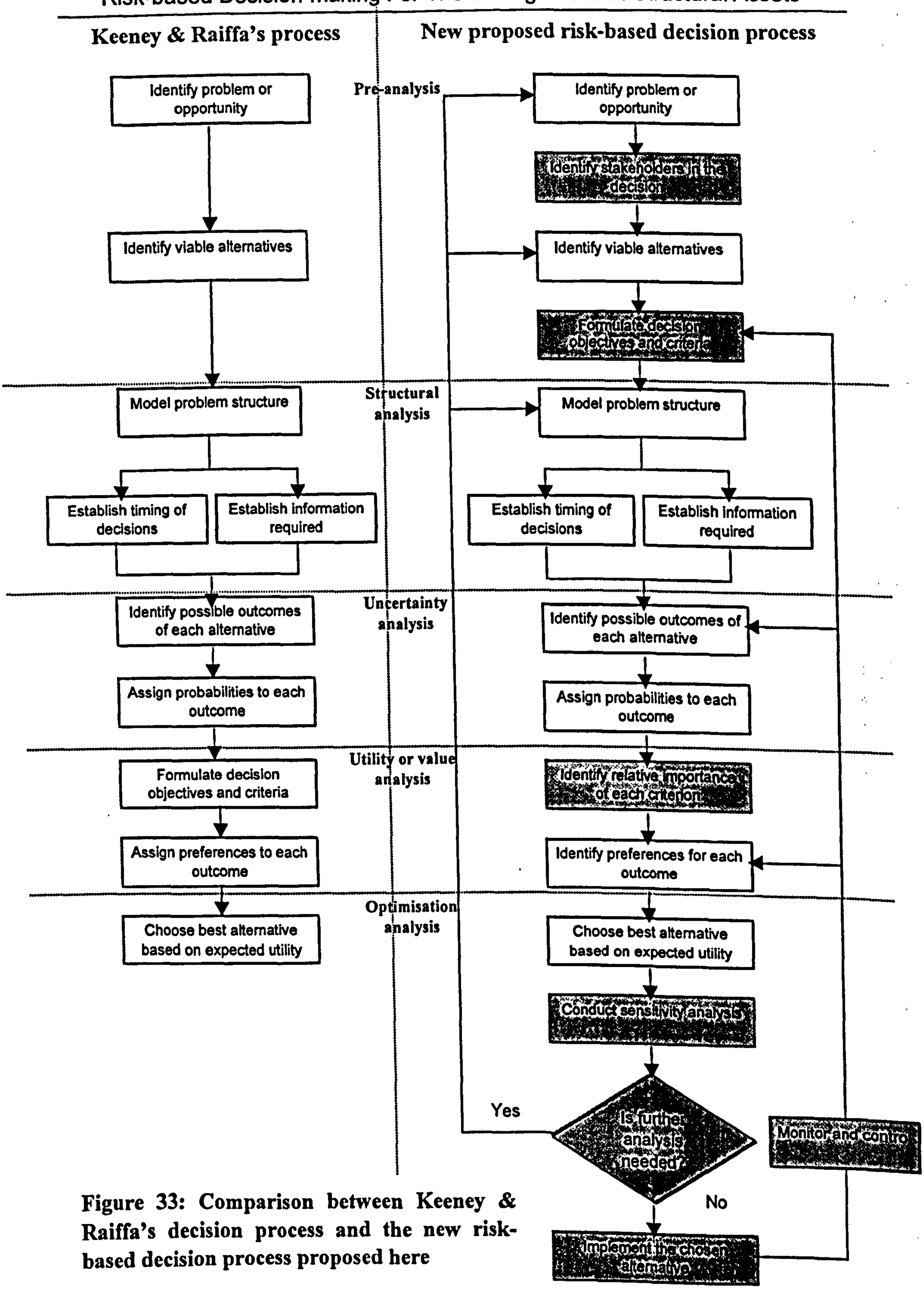


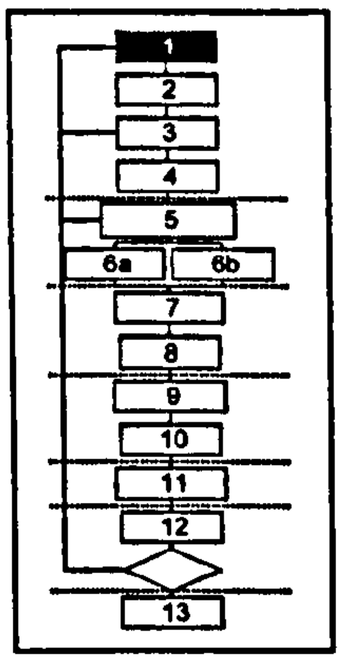
Figure 33: Comparison between Keeney & Raiffa's decision process and the new risk-based decision process proposed here

Process Stage	Activity	Case 1 Feasibility of re-using subsea facilities in new developments	Case 2 Developing a maintenance strategy for viaduct crossbeams	Case 3 Planning pipeline repair & replacement schedules	Case 4 Prioritising bridge strengthening works	Case 5 Review of risk-based decision-making in APA (Project Decisions)	Case 5 Review of risk-based decision-making in APA (Design Decisions)
Problem Definition	Identify problem or opportunity	Identified by Installation Contractor	Identified by Operator	Identified by Operator	Identified by Operators	Often the problem was not identified until after the decision was made	Identified by the operator or the installation contractor
	Identify stakeholders in the decision	N/A	Considered initially	Accounted for qualitatively	Accounted for quantitatively	Important but not included in the decision	Important but not included in the decision
	Identify viable alternatives	Alternative Concepts Identified	Vast number of strategies combining different maintenance/ repair options /crossbeams /repair dates	Two alternative concepts identified for consideration	Vast number of strategies combining different maintenance/ repair options/ bridges/ repair dates	Minimal or no alternatives generated for each decision	In some cases, brainstorming generated alternatives, in other cases, alternatives were limited
	Identify decision objectives and criteria	Simplified to Expected Cost of Installation	Minimise "risk of failure" within allocated budget	Minimise risk, OPEX and CAPEX	Minimise risk, traffic disruption, social impact, cost of repair, maximise additional benefits	Most decisions were made based on minimising short term costs and short term risks	Most decisions were made based on minimising short term costs and short term risks
Structural Analysis	Model problem structure	Detailed Decision Tree for each Alternative	Too complicated for decision tree and not sufficiently represented by an influence diagram	Qualitative Decision Tree for the two alternatives	Too complicated for decision tree and not sufficiently represented by an influence diagram	No structural analysis carried out	No structural analysis carried out
	Establish timing of decisions	Identified Qualitatively at stages of removal and re-installation	Decisions made now and updated following inspections	Decision made now and updated following inspections	Decisions made now and repeated each year	Decisions were made for the short term.	Decisions were made for the short term
	Establish information required	Subjective estimates of cost used	Detailed costings of repair options and budget forecasts	Cost Estimates of the two alternatives	Cost estimates of each bridge repair strategy, assessment of traffic disruption and social impact based on detailed questionnaire	Minimal effort used to obtain or review data; assumptions were made instead. Even when data was available, it was not used well	In some cases, a detailed review of available data was carried out. In other cases, even given data was ignored.

Process Stage	Activity	Case 1 Feasibility of re-using subsea facilities in new developments	Case 2 Developing a maintenance strategy for viaduct crossbeams	Case 3 Planning pipeline repair & replacement schedules	Case 4 Prioritising bridge strengthening works	Case 5 Review of risk-based decision-making in APA (Project Decisions)	Case 5 Review of risk-based decision-making in APA (Design Decisions)
Uncertainty and Probabilistic Analysis	Identify possible outcomes for each alternative	Based on expert opinion	Three failure modes identified	Two failure modes considered	Based on deterministic code assessment and expert opinion	The significant risks and uncertainties were not identified.	Short-term installation risks were recognised. Long term risks ignored
	Assign probabilities to each outcome	Subjective estimates of probability used	Detailed structural reliability analysis over time	Detailed probabilistic corrosion modelling over time	Risk index used to simply evaluate risk of failure	When the uncertainties were recognised it was in a biased way	Qualitative assessments of some risks were used
Utility/Value Analysis	Identify relative importance for each outcome	N/A	Consequences were common to all alternatives, so main criteria was failure probability	Minimising risk taken as the main decision criteria	Detailed interviews of stakeholders to establish weightings for each criteria	The main decision criteria were short term issues such as cost savings and minimising risk	Minimising risk and installation cost were taken as the main decision criteria
	Identify preferences for each outcome	N/A	Minimum acceptable reliability identified	Leak/failure considered unacceptable by all stakeholders	Detailed interviews of stakeholders to establish risk acceptance levels	Stakeholder preferences were ignored, so the decision was not best for the operator.	The preferences of the installation contractor biased the decisions
Selection of Best Alternative	Choose best alternative based on expected utility	Based on minimum expected cost	Detailed decision rationale built to combine alternative options into optimised strategies	Based on minimum risk of failure	Based on maximising the multi-attribute ranking	Based on strong biases. The consequences showed the lack of rationality.	Based on minimum installation cost and risk or just on the contractor's preferences
Sensitivity Analysis	Conduct sensitivity analysis	Recommended based on different estimates of cost and probability	Carried out to identify important uncertain variables, to recommend model refinement	Not carried out due to extremity of results	Carried out to identify effect of stakeholder preferences	No sensitivity analysis carried out.	No sensitivity analysis carried out
	Conduct further analysis if required	Not carried out at this stage	Not carried out at this stage but could be repeated following improved data/models	Not carried out at this stage but would be repeated following further inspections	Not carried out at this stage, but possible if consensus was poor	No further analysis carried out.	No further analysis carried out
Implementation	Implement the chosen decision	Solution recommended by contractor if the field development was initiated.	Solution recommended by consultant after I left the project	Solution recommended and accepted by all stakeholders	Solution recommended and accepted by all stakeholders	Best Solutions were not necessarily recommended.	Most of these decisions were not made in the best interest of the operator.

Table 65Comparison of five case studies against the proposed decision process

11.1 Identify the Problem or Opportunity



Comparing the first four case studies in terms of the proposed decision process shows that the decision problem was recognised and addressed by the primary decision-maker in each situation. In case study 1 (feasibility of re-using subsea facilities in new developments), the decision-maker was the installation contractor rather than the operator because of the timing of the decision. The installation contractor, in preparing two separate tenders to two separate operators, identified the opportunity of reusing one operator's facilities in the second operator's development.

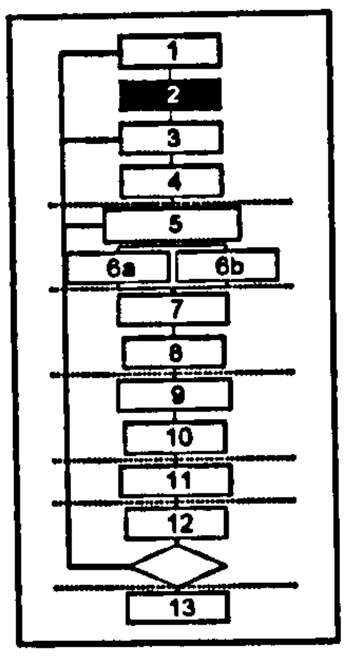
In case studies two to four (developing a maintenance strategy for viaduct crossbeams, planning pipeline repair & replacement schedules and prioritising bridge strengthening works) the operator identified the problem as a result of discovering, through routine inspections and assessments, that the structure no longer conformed to the statutory codes and standards. The structures therefore required some form of remedial attention. The decision-maker was then faced with at a least two initial alternative actions, which appeared complex and conflicting. This raised awareness of the need to address the problem rationally.

Comparing these four cases against case study 5 (review of risk-based decision-making in APA) reveals that without knowledge or experience of the proposed decision process, decisions are often made subconsciously, without even realising at times that a decision is required. This problem is more pronounced in the project management decisions, where "non-decisions" are made by "drifting" into a solution of an unidentified problem. In these situations, the decision-maker often has no awareness of the problem or opportunity that lies before him/her and therefore does not recognise the alternative solutions available to maximise the benefit from the situation. An example of this was the decision to withhold project members from full participation into the integrated project team. It appears that this was more of a non-decision because management wanted to avoid the logistical problems of seconding staff out of the office. It is unlikely that management made a definite decision to limit the input to the project team. An even worse situation occurs when the wrong problem is identified, as in the decision to select a project manager. This was not the decision problem. The problem was one of how to control the project to satisfy the clients needs at maximum margin for APA and with minimum disruption to other projects and clients. If the problem had been identified clearly, different alternatives might have arisen and it would have been possible to control and attain the objectives. This situation is less severe for the design decisions, as there is typically a real engineering decision to be made and thus is recognised by the design engineer responsible.

Project management decisions, being less quantitative than design decisions, are more likely to be made through some form of evolution rather than by a clearly evaluated selection. The presence of the proposed risk-based decision process and experience of its use can prompt decision-makers to recognise problems and opportunities before a

potentially sub-optimal solution evolves. It can therefore be concluded that the availability of the risk-based decision process helps the decision-maker to recognise the problem or opportunity facing them. It also to gives an indication, even at such an early stage, of how to gain the most benefit from the identified decision.

11.2 Identify Stakeholders in the Decision



It can be seen from Table 65, that the effort involved in the identification and evaluation of the stakeholders in the decision depends on the position within the life cycle. It also depends on the number and strength of conflicting opinions that are influencing the decision, especially where environmental or political issues are key. In case study 1 (feasibility of re-using subsea facilities in new developments), the decision was very conceptual and was taken at a early on in the life cycle. The decision was therefore made on qualitative information and expert opinion. Making the decision at a conceptual level also removed the politics from the decision, since the stakeholders did not perceive it as final. This meant that the stakeholders were not a major consideration in this decision. For case studies 2, 3 and 4, the decisions were taken much later on in the structure's life and more information was therefore available. This meant that the stakeholders were considered in more detail. In contrast, in case study 2 (developing a maintenance strategy for viaduct crossbeams), initial assessment revealed a straightforward consensus between the stakeholders concerning minimising risk of failure and total cost, it followed that detailed stakeholder analysis was not required. In case study 3 (planning pipeline repair & replacement schedules) there was initially some political disagreement. However, focus on the common decision criteria allowed consensus to be built. Case study 4 (prioritising bridge strengthening works) involved far more conflict and therefore required a detailed process for building consensus amongst the conflicting stakeholders. The risk-based decision process allowed this to be carried out in an open and auditable manner, creating ownership of the decision at all levels. For conceptual level decisions therefore, it is rarely necessary to consider stakeholder influences, however for detailed decisions these factors become more important. Figure 34 shows a matrix to help the decision facilitator determine when to account for stakeholder influences.

These case studies have showed that the use of the risk-based decision process provides a prompt for stakeholder issues to be considered. It also helps determine whether a more detailed assessment of influences and preferences should be made. Case study 5 (review of risk-based decision-making in APA) highlighted this benefit further. The absence of the decision process while these decisions were made meant that the best solution was not sought on behalf of all stakeholders. This shortcoming was further magnified by the current trend in industry to delegate design and maintenance decisions to contractors. Typically contractors benefit from the decisions they make in the short term only, through reduced risk and costs and increased profits. They do not have, therefore, any incentive to make decisions for the long-term benefit of the owner or operator. Although the operator also benefits from control of the CAPEX and by

minimising the exposure to installation risk, he is also exposed to operational costs and risks throughout the lifecycle. For example in the decision of whether to trench the pipeline or not, the consideration and evaluation of all stakeholder influences and preferences would have stopped the contractor from installing an inoperable pipeline just because of the low installation costs. It can be concluded, therefore, that it is the availability of the risk-based decision process that prompts the consideration and evaluation of stakeholders' influences and preferences in the decision. This allows the overall best decision to be made to suit all of the parties involved.

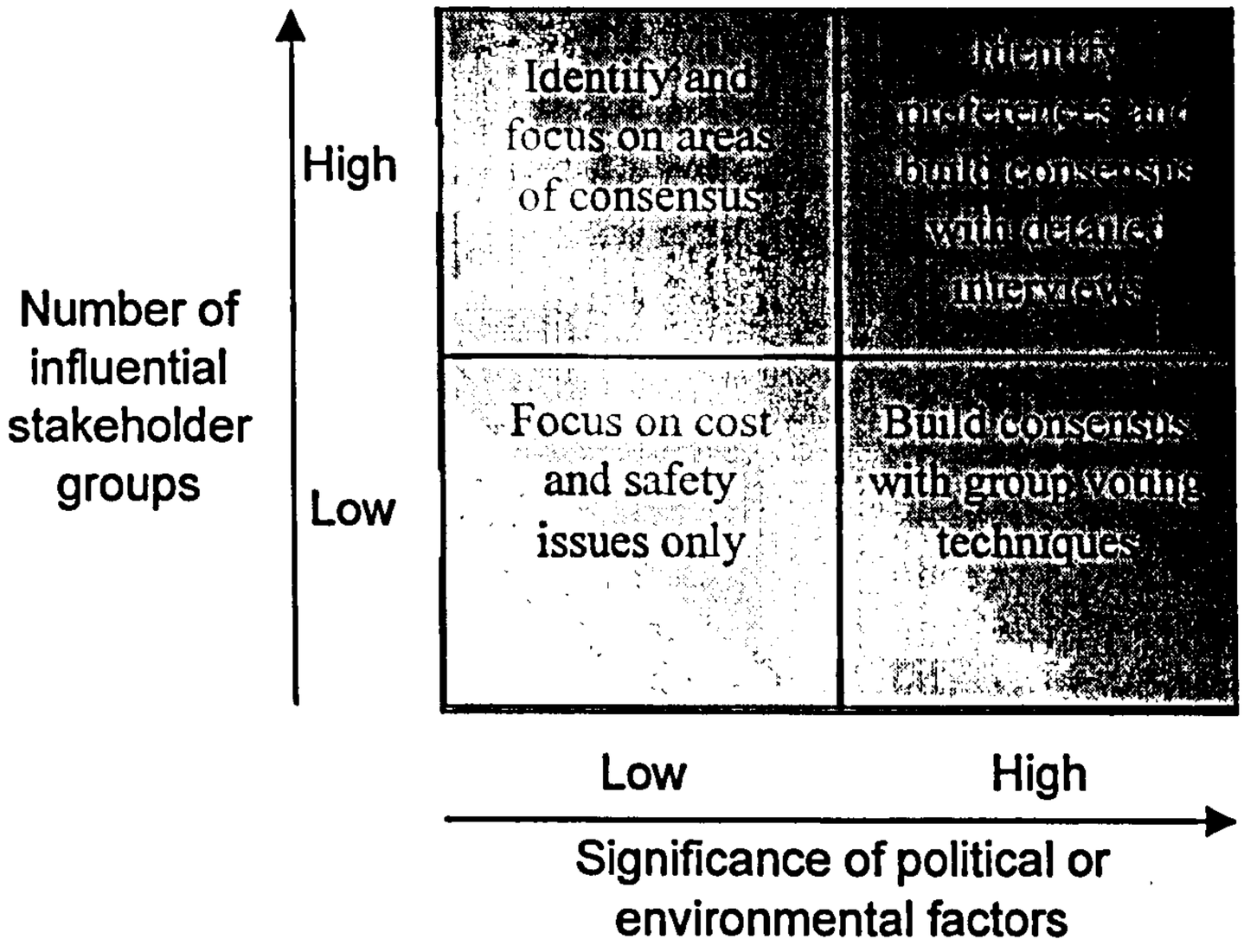
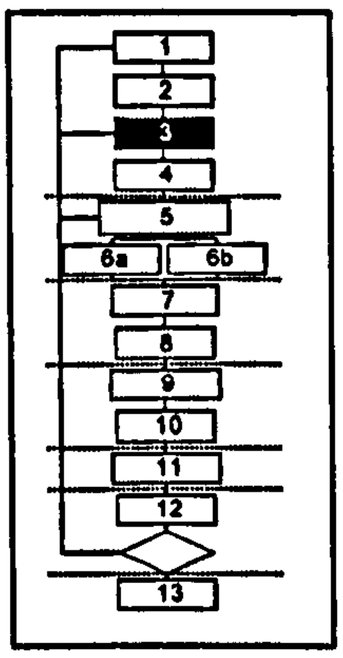


Figure 34 Matrix for determining stakeholder influences

11.3 Identify Viable Alternatives



Experience from the first four case studies showed that it was not always possible to identify all of the available alternatives, and even when it was possible it was not always necessary or even desirable. In some cases, such as case studies 2 (developing a maintenance strategy for viaduct crossbeams) and 4 (prioritising bridge strengthening works), there were a near infinite number of combinations of actions that could have been identified. These case studies begin to approach the "design" type decision problems described in the literature review, which could be solved by using optimisation algorithms. In practice, the difficulties associated with developing a suitable optimisation algorithm can be prohibitive; and decision-makers frequently prefer to adopt evaluation techniques for design decision problems. In an evaluation decision problem each alternative can be clearly defined and can therefore be evaluated in the context of the environment of the problem. This stage in the decision process, therefore, requires the decision-maker to realise the alternatives available and identify a strategy for considering them. The more alternatives that can be identified, the greater will be the

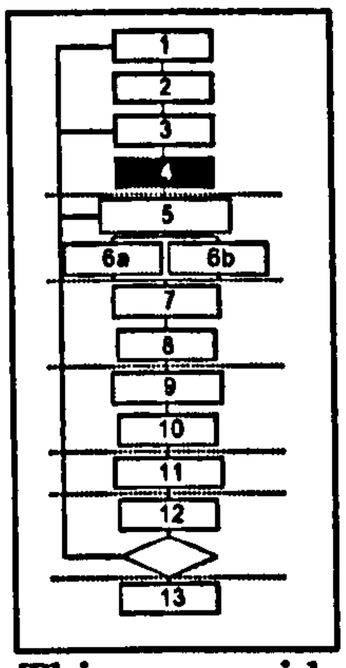
opportunity to optimise the decision in terms of risk and therefore fulfil the ALARP criteria. Experience from the case studies indicate that the most successful methods for generating alternatives are the range of brainstorming techniques presented in Chapter 4, this conclusion is supported by the literature, for example [85].

In case study 2 (developing a maintenance strategy for viaduct crossbeams), a supporting decision rationale had to be developed. This was required to take account of a number of different factors such as the timing, the budgeting and the cost benefit of carrying out repairs sooner rather than later. In contrast, for case studies 1 (feasibility of re-using subsea facilities in new developments) and 3 (planning pipeline repair & replacement schedules), the alternatives were considered at a more conceptual level to establish the most appropriate concept to adopt. This allowed more detailed evaluation of the "sub-alternatives" later. Case study 5 (review of risk-based decision-making in APA) revealed the problems that arise when an assessment of the alternatives is not carried out. In such cases it is almost guaranteed that sub-optimal decisions will result. Even if the decision-maker has significant experience of similar situations, it does not follow that past solutions will be the best in a new situation. The problems associated with a failure to identify appropriate alternatives were more pronounced in the project management decisions than in the design decisions. This was due to the decision-maker holding a limited view of the problem in hand. Some of the design problems did involve some form of brainstorming to try to identify more design alternatives.

Experience is not always an advantage in these decisions. It can blinker the decision-maker to only considering alternatives that have been experienced before (even if the situation is different). Experience and expertise may, therefore, constrain innovation and creativity. The benefit of the risk-based decision process is that it encourages the decision-maker to step outside his/her limited experience and to consider the decision problem with creativity (through lateral thinking, brainstorming, etc.). This makes it more likely that many, if not all, of the possible alternatives are taken into account in the decision.

The simpler methods for generating alternatives, such as attribute listing and brainstorming tend to be the most appropriate in these "evaluation" type decisions as they involve little methodology for a potentially high output. In addition, the availability of interactive software to support brainstorming helps to make the process less tedious for the decision-makers involved. Screening methods can then be used to reduce the set of alternatives again to remove any that are unfeasible, unacceptable or dominated by others.

11.4 Identify Decision Objectives and Criteria



Based on the limited experience from the five case studies, it would appear that, more often than not, decisions are made in terms of cost and safety risk only. Often, this is because the consequences of failure are almost automatically quantified in terms of cost. I think that this is because it appears to be a more straightforward approach due to the way that problems have been tackled in the past. Decision-makers frequently, do not feel confident at quantifying all consequences in terms of cost. Doing so is an inherently difficult and possibly contentious task and, given the opportunity, the decision-makers would quantify the consequences in their natural units for as long as possible. This was evident in case study 4 (prioritising bridge strengthening works). Each of the stakeholders interviewed for their preferences found it easier to quantify acceptable consequences in terms of their natural units. In addition, they also found reassurance in the way the consensus was built up. They could see that the different criteria were accounted for and weighted according to the preferences of each of the stakeholders. In case study 4, due to the political and contentious nature of the problem, there was a clear desire by the stakeholder to take the more qualitative factors into account, therefore multi criteria decision methods were of real benefit. The number and type of decision criteria to be used to solve a decision problem can be determined based on this experience. For structural management decisions, the number and type of decision criteria depend on the range and severity of the consequences of failure and the strength of stakeholder influences as shown in the matrix in Figure 35.

Case study 5 (review of risk-based decision-making in APA) showed how the default decision criteria, without the support of the decision process, tend to be short-term risks and costs. They are short-term evaluations because it is very difficult to quantify these consequences in the longer term, without any decision support, especially since the uncertainties increase with time. However, the considered risks are only short term because often these are the only risks that affect the decision maker (who is often the installation contractor), all long term risks are transferred to the operator who has no influence in the decisions. Only risks and costs are considered because they are the easiest consequences to quantify without an understanding of multi-criteria methods. Such limitations on decision criteria can result in sub-optimal decisions with extensive consequences beyond financial costs. For example, the environmental, social or political consequences, none of which were identified in the decision and all of which affect a wide range of stakeholders. Alternatively, the adverse consequences of a decision may only become apparent in the longer term. This was so in the case of the pipeline design where a cooling spool was introduced. The increased cooling rate resulted in major operational problems. The ability of the risk-based decision process to allow a more diverse range of decision factors therefore brings more clarity to the decision process. It also brings more flexibility for those decision-makers who have previously been constrained to trying to quantify all consequences in terms of cost.

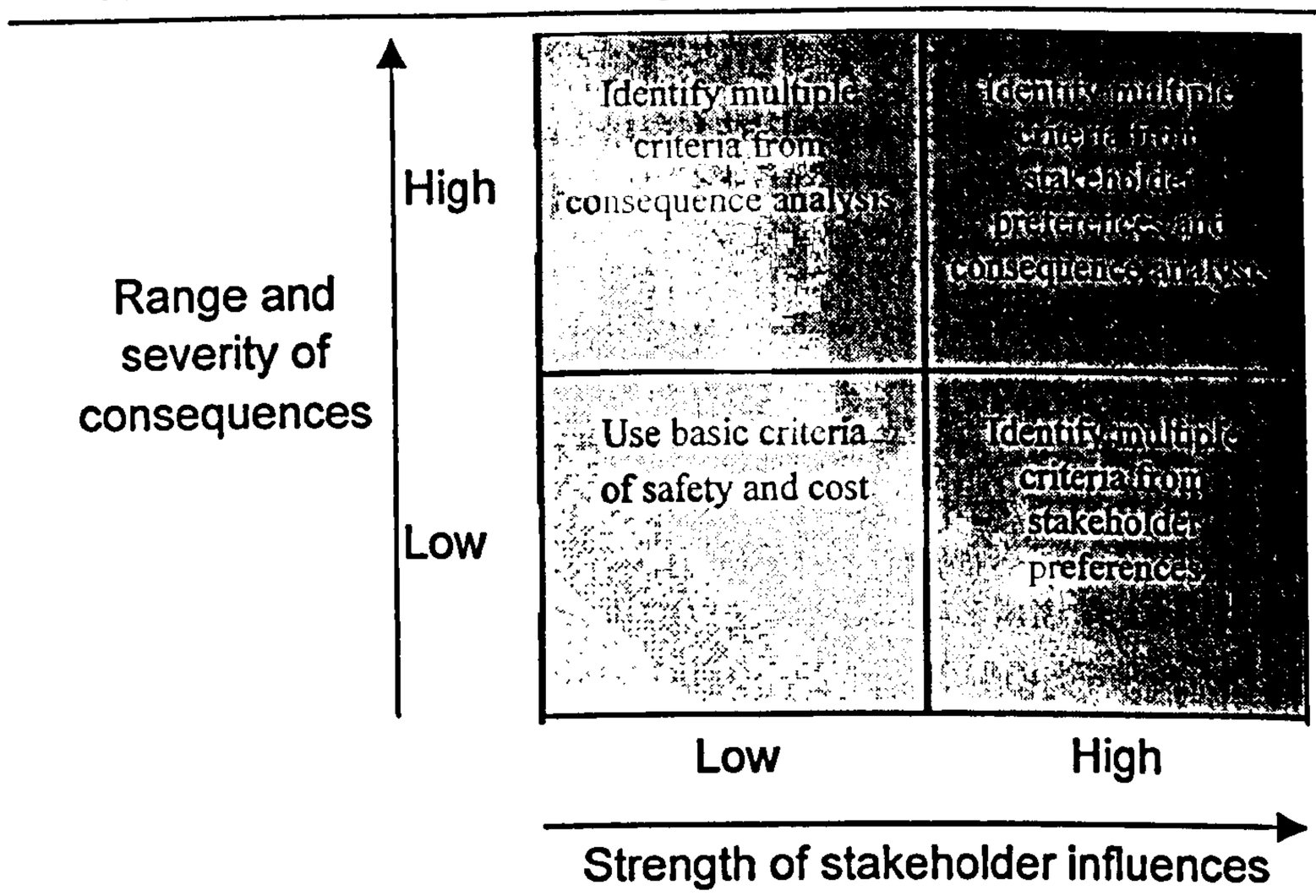


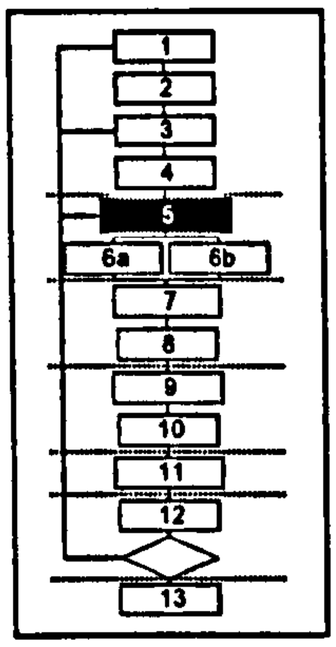
Figure 35 Matrix for determining the number of decision criteria

In 1993 the HSE examined the use of quantitative risk assessments in supporting decision-making [160]. The paper reviewed the criteria used in decision making and it was suggested that decisions are made by qualitatively accounting for societal risk in addition to individual risk. The criteria that were considered to affect the tolerability of risk included:

- The nature of the risk.
- The nature of the human consequences.
- Potential economic benefits.
- The nature of the risk assessment.
- Factors affecting the risk generator.
- Public attitudes towards the risk.
- Public confidence in the authorities.

The working party responsible for this paper concluded that a large number of qualitative criteria are accounted for in the decision process. Although their work was focussed on the nuclear industry, a number of the major decisions they investigated were from other industries including transport and oil and gas. The HSE made no attempt in their work to recommend methods for quantitatively accounting for these factors but they did suggest that this was necessary to make these decisions more rational and auditable.

11.5 Model Problem Structure



The case studies have shown that a decision tree can be a useful tool for the definition of a problem. However, it is not always necessary to use one. For example, in case studies 2 (developing a maintenance strategy for viaduct crossbeams) and 4 (prioritising bridge strengthening works), the numbers of alternatives available were too great for any benefit to be gained from the huge decision trees that would have resulted. Decision trees were found to be beneficial in considering the decision problems conceptually, but could not be used to solve the problems. Case studies 1 (feasibility of re-using subsea facilities in new developments) and 3 (planning pipeline repair & replacement schedules), having much fewer alternatives, benefited much more from using decision trees to evaluate each alternative and each consequence. Case study 1 was in fact solved entirely with a decision tree. Case study 1 was such a straightforward decision in terms of alternatives. However, because of the number of possible outcomes over time, the tree still grew to a size that was only just manageable. It can be seen therefore, that there is a size limit above which a decision tree becomes too cumbersome to be useful although the availability of computer software provides some support.

An alternative to using a decision tree is to use an influence diagram, described in Chapter 4. This approach was found to be very useful for representing the main concepts of even the most complex decision problems and identifying all interactions between decision criteria, uncertainties and input values. The influence diagram was found to help the decision-maker articulate the decision problem and identify all the alternatives, even though it does not represent the same level of detail as a decision tree. This was found to be especially true for case study 4.

Both of these structuring methods have been found to be extremely useful for communicating the decision problem to other stakeholders and gaining their input into the problem formulation. Figure 36 shows a matrix to help the decision facilitator select the most appropriate method for structuring the decision problem.

Case study 5 (review of risk-based decision-making in APA) revealed how rarely these powerful tools are applied in practice despite the benefits and clarity they can bring. There is evidence in nearly all of the examples of the decisions not being clearly formulated or communicated and therefore resulting in sub-optimal decisions. It can therefore be concluded that by using the proposed risk-based decision process, the decision-maker is prompted to formulate the decision with the use of the decision tree/influence diagram. This then ensures a logical and thorough formulation, which can be clearly communicated, to the stakeholders. It is however, only in simple decisions that the decision tree/influence diagram can be used to solve the decision problem. In most decisions they are the tools through which the issues are collated, clarified and communicated to the stakeholders before the detailed analysis is carried out.

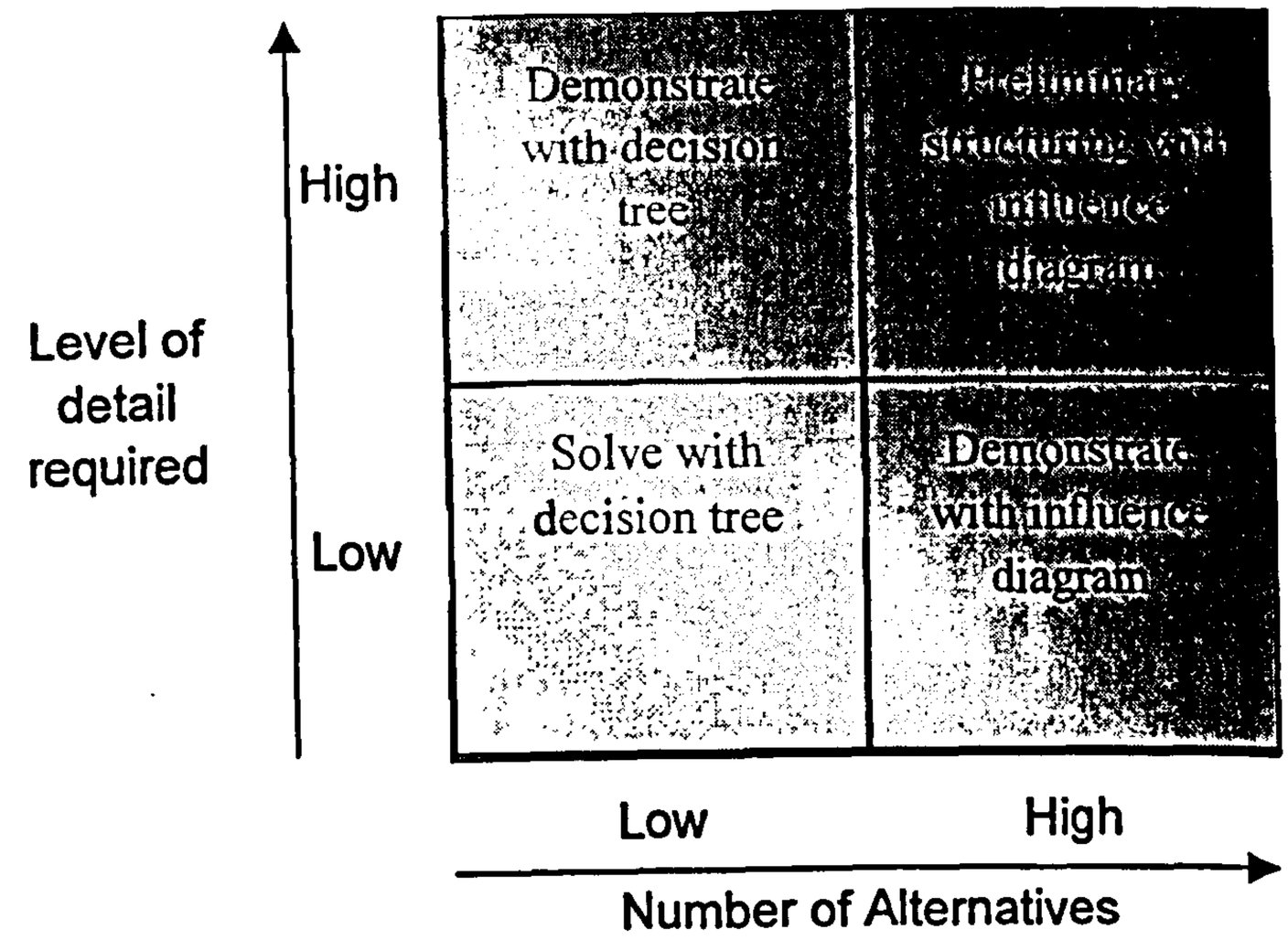
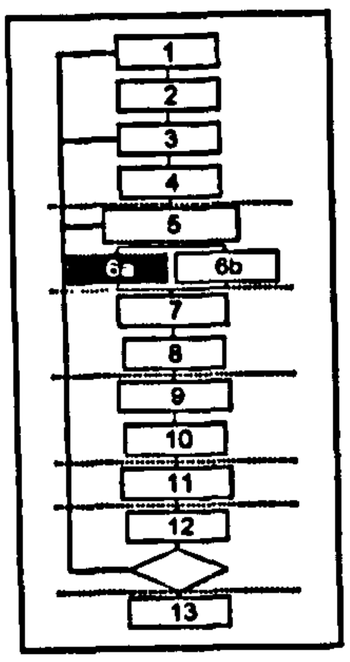


Figure 36 Matrix for the method of structuring the decision problem

11.6 Establish Timing of Decisions

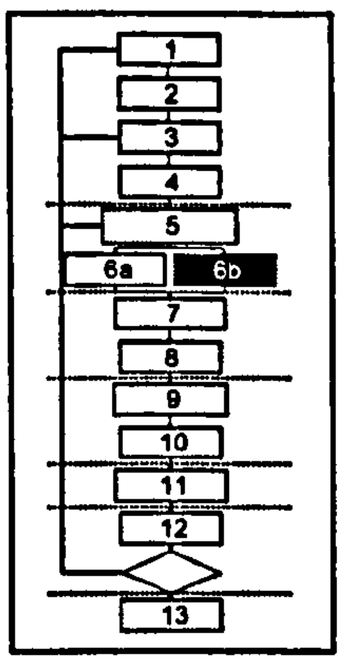


This stage of the decision process is one of the steps recommended by Keeney and Raiffa [23]. During the design stage, the timing of decisions is key to the effectiveness of their implementation. If they are delayed, then it can be very difficult to have the identified features included. Most of the decisions evaluated in case studies 1 to 4 were mid life decisions, at these stages, timing does not always have such a major role to play in the decision, but when it does, the difference to the decision is significant. For example, most mid-life decision problems are not identified until it is already time to make the decision. Case studies 2, 3 and 4 all addressed problems which needed an action immediately, but were also affected by timing. Case study 2 (developing a maintenance strategy for viaduct crossbeams) needed an immediate decision of the safety of the bridge crossbeams, but a delayed decision of the time for maintenance. Obviously, those that were already considered unsafe needed the repair decision to be made immediately, but for those that were still safe a provisional repair scheduling decision could be made and revised following further inspections. Such timings if accounted for in the decision process help optimise the allocation of resources over time.

In case study 5 (review of risk-based decision-making in APA), several of the examples showed that the timing of decisions was not used to the best advantage and decisions were made before all the information was available. In some cases, this occurred even in the knowledge that the information would become available later. The consequence of this was a number of sub-optimal decisions, which might have had better outcomes if they had been made later once the information was available, although this may have then affected the project schedule with resultant financial consequences. Therefore, although it appears initially to be a very small consideration within the whole decision process, accounting for the timing of the decisions can play a very significant role in

determining how well the decision is made. This is therefore a very important step in the decision process that should not be ignored.

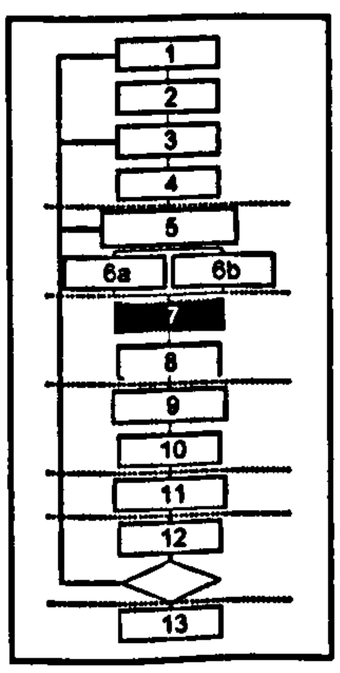
11.7 Establish Information Required



This stage in the decision process is very closely linked with the previous stage, in that obtaining necessary information on which to base the decision can affect the timing of the decision and timing determines what information is available. Information is the key to all decision-making and risk assessment. It is therefore essential to assess the information required to support the decision-making and examine the benefits that specific pieces of information will bring. Case studies 1 to 4 all considered the information that was easily available and the information that could be obtained, sometimes at a cost, if it were required. In case study 1 (feasibility of re-using subsea facilities in new developments) the decision was based on expert opinion, since this was considered to be sufficient at that point in the project life-cycle. The decision process did, however, identify that there would be value in obtaining further information in some areas. Case studies 2 and 4 followed a similar pattern where a preliminary evaluation allowed the requirements for a more detailed assessment to be identified. Once a decision is made, it is possible to assess the need for further information such as new inspection data, at a later date, to update the analysis and even, if necessary, to modify the decision. This was the situation in case study 3 (planning pipeline repair & replacement schedules) where a decision on the need to replace the pipeline could be made on currently available data. However further inspection and monitoring were required to provide confidence in the pipeline's continued operation until a replacement could be installed.

In case study 5 (review of risk-based decision-making in APA) there were a number of occasions where decisions were made without using all the available information or even without identifying all the information that was available. This means that, in hindsight, the decision appears to be illogical and certainly sub-optimal. It is clear therefore, that it is important that a decision should be based on the maximum available information, and that the cost benefit of obtaining further information should be examined. Only if this activity is undertaken is it possible to demonstrate that the final decision is robust.

11.8 Identify Possible Outcomes for each Alternative

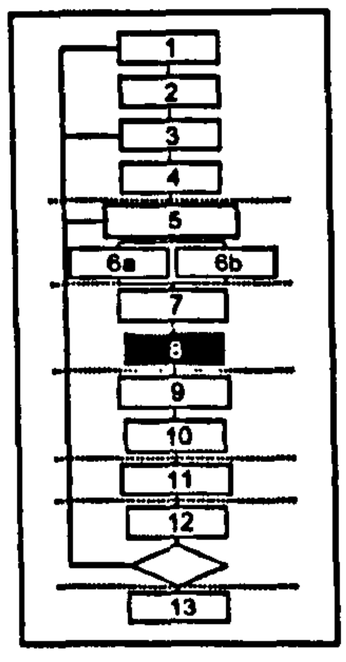


Identifying the possible outcomes for each alternative involves answering the question "what could go wrong and how wrong could it go?" Experience from the first four case studies revealed how important it is to identify and assess all significant failure modes and the consequences of those failure modes. This allows the right emphasis to be placed on either mitigating against failure or providing contingency in the case of failure. In case study 1 (feasibility of re-using subsea facilities in new developments) it was sufficient to identify the risks based on expert opinion since the decision was made

at a very conceptual level and involved a number of operational risks as well as structural risks. In case studies 2 to 4 however, the risks were far more significant, involving more complex failure modes and potential consequences which included loss of life. Structured brainstorming techniques were found to be useful at this stage to draw on the experiences of a wide number of experts and ensure that as many potential risks as possible are identified and accounted for in the decision. These methods were discussed in Chapter 4.

Case study 5 (review of risk-based decision-making in APA) revealed that an evaluation of the outcomes does not always take place. A number of the decisions have resulted in outcomes that were totally unexpected at the design stage. Unexpected outcomes are generally unwelcome and can be very expensive, especially for the long-term operator of the asset. In the case of the decision to trench the pipeline and then to introduce a cooling spool, the outcome was a pipeline with impaired operability. If a full risk evaluation undertaken, even after the decision to trench had been made, these consequences may have been foreseen and the decisions modified accordingly. Instead, the operator has a long-term operability problem as long as the pipeline remains in use. This situation makes the point very clear and highlights the absolute necessity of seeking to identify and account for all possible failure modes and consequences of the decision before it is too late. The need for thorough and detailed risk identification tools is therefore essential.

11.9 Assign Probabilities for each Outcome



Of equal importance to the identification of all possible outcomes is the assessment of the probability of each outcome. Once again, the detail with which this is carried out depends on the type of decision and the amount of information available. In case study 1 (feasibility of re-using subsea facilities in new developments), because the decision was made at a conceptual level, it was sufficient at this stage to base the probabilities on experience. It would have been appropriate to refine these estimates if the decision had been taken further. For case studies 2 (developing a maintenance strategy for viaduct crossbeams) and 3 (planning pipeline repair & replacement schedules) safety was a very important issue. It was therefore, necessary to demonstrate confidence in the evaluation of the probabilities. The detailed reliability analysis based on the statistical data that was available provided a thorough evaluation of the probability of failure for each failure mode. In case study 4 (prioritising bridge strengthening works) safety was again a significant issue. However, the amount of effort that would have been required to carry out detailed reliability analysis of each alternative was prohibitive (due to the many different structural forms and hence failure modes). The risk scoring system provided a useful approximation based on the deterministic code assessment results and provided a level of accuracy appropriate to the context of the problem. Figure 37 shows a matrix which gives guidance to when a detailed reliability analysis is required and when a more subjective assessment is considered acceptable.

Once the evaluation of the probability of failure has been made, irrespective of how subjectively, it is possible to remove certain outcomes from the assessment, to simplify the problem. These outcomes should only be removed if they have a very low probability and a very low consequence. In case study 5 (review of risk-based decision-making in APA), the decision-maker ignored some risks, which were not of low probability or of low consequence, or transferred them to another stakeholder. The decision-maker (often the contractor) preferred not to acknowledge these risks, in order to avoid the need to mitigate against them, and transferred them back to the operator. Problems arose later when unexpected outcomes occurred, creating additional costs for the operator to cover. These should have been identified and evaluated at the time the decision was made in order to allow the operator to fully understand the implications of the risks and to mitigate against them.

The risk-based decision process, in involving all stakeholders throughout each stage of the decision, ensures that the consequences and probabilities of all possible outcomes are evaluated in the interest of all stakeholders. This provides a full understanding by all parties and helps to build up consensus in the decision that is made.

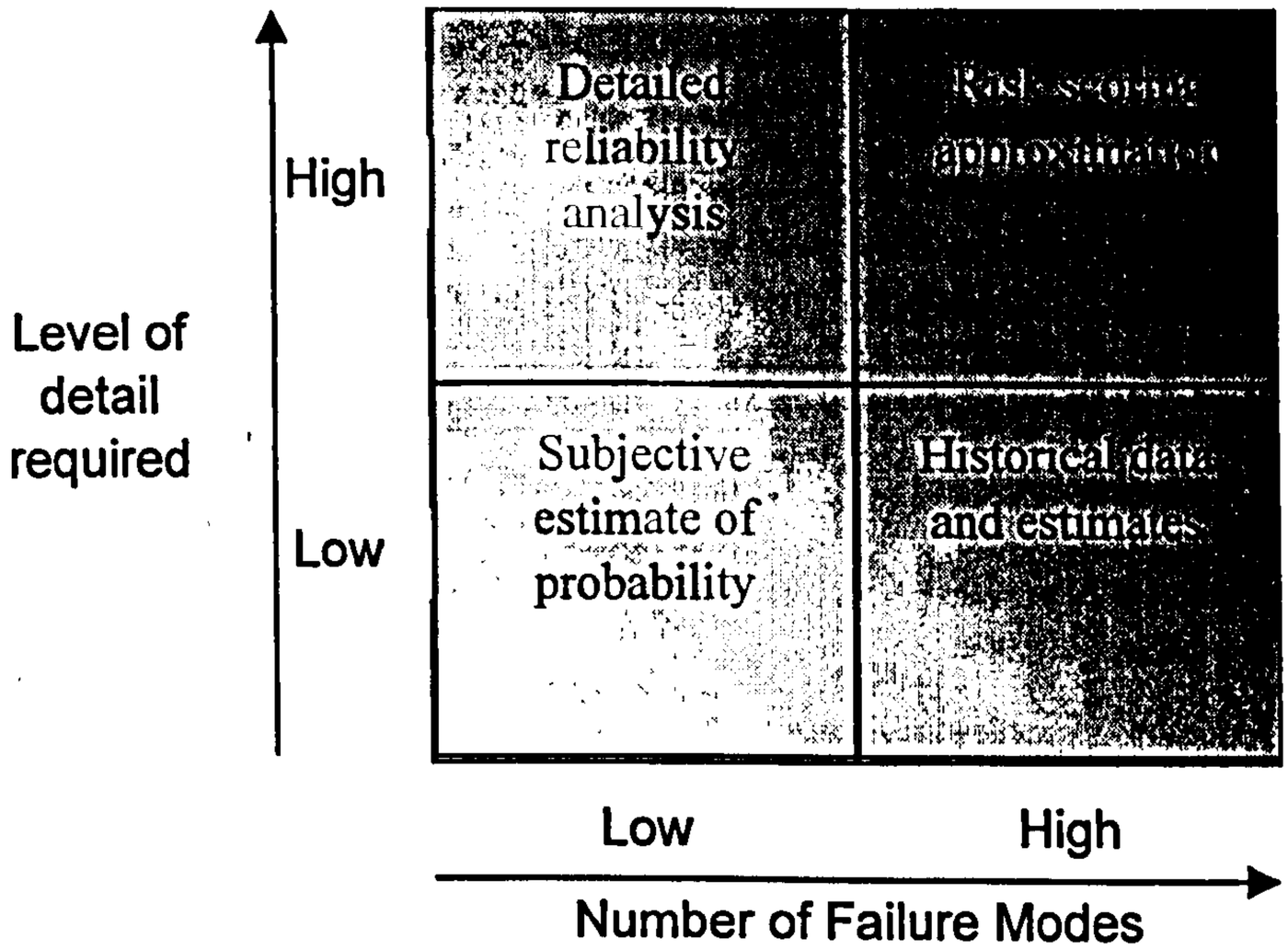
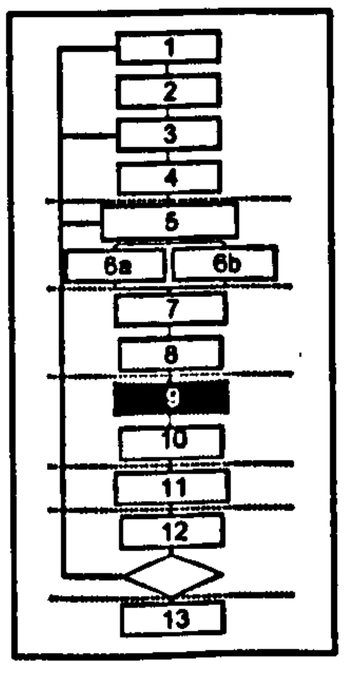


Figure 37 Matrix for the method of evaluating probability of failure

11.10 Identify Relative Importance for each Outcome



It is not always necessary to quantify specific weightings for each decision criteria, especially when only one or two criteria are considered. In these cases, gaining consensus from the stakeholders of which criteria, if any, should dominate is a useful clarification of the decision process. In case study 1 (feasibility of re-using subsea facilities in new developments) the decision was made at such a conceptual level, based on only two decision criteria, that these criteria were taken as having equal importance. Similarly, in case studies 2 (developing a maintenance strategy for viaduct crossbeams) and 3

(planning pipeline repair & replacement schedules), it became clear very quickly, from discussion with the stakeholders, that the dominant criterion was risk, with cost being a constraint. It followed that it was not necessary to quantify weightings for the criteria. In contrast, in case study 4 (prioritising bridge strengthening works) five main decision criteria were considered, plus additional sub-criteria. There were also a large number of conflicting stakeholder views. It was therefore important, in order to build consensus, to evaluate in detail the relative importances of the criteria through detailed consultation with the stakeholders. This was time consuming, as each stakeholder interview took on average 2 hours, and interview preparation and post-processing took around a week to complete. However, the overall decision-maker considered this effort worthwhile, since it achieved consensus and thereby ensured buy-in for the final decision.

Case study 5 (review of risk-based decision-making in APA) revealed that the decision-makers identified the main decision criteria in accordance with their own preferences, without consultation with other, potentially important stakeholders, such as the operator. Frequently, decision criteria, even if they were important, were ignored if they were difficult to quantify.

The risk-based decision process causes the decision-maker to actively consider which decision criteria to use and how to quantify their relative importances. This means that identified decision criteria will be ignored only following an explicit decision to do so, and that such decisions would be auditable. Figure 38, shows how different numbers of stakeholder views and different numbers of decision criteria affect the way in which criteria weightings should be identified.

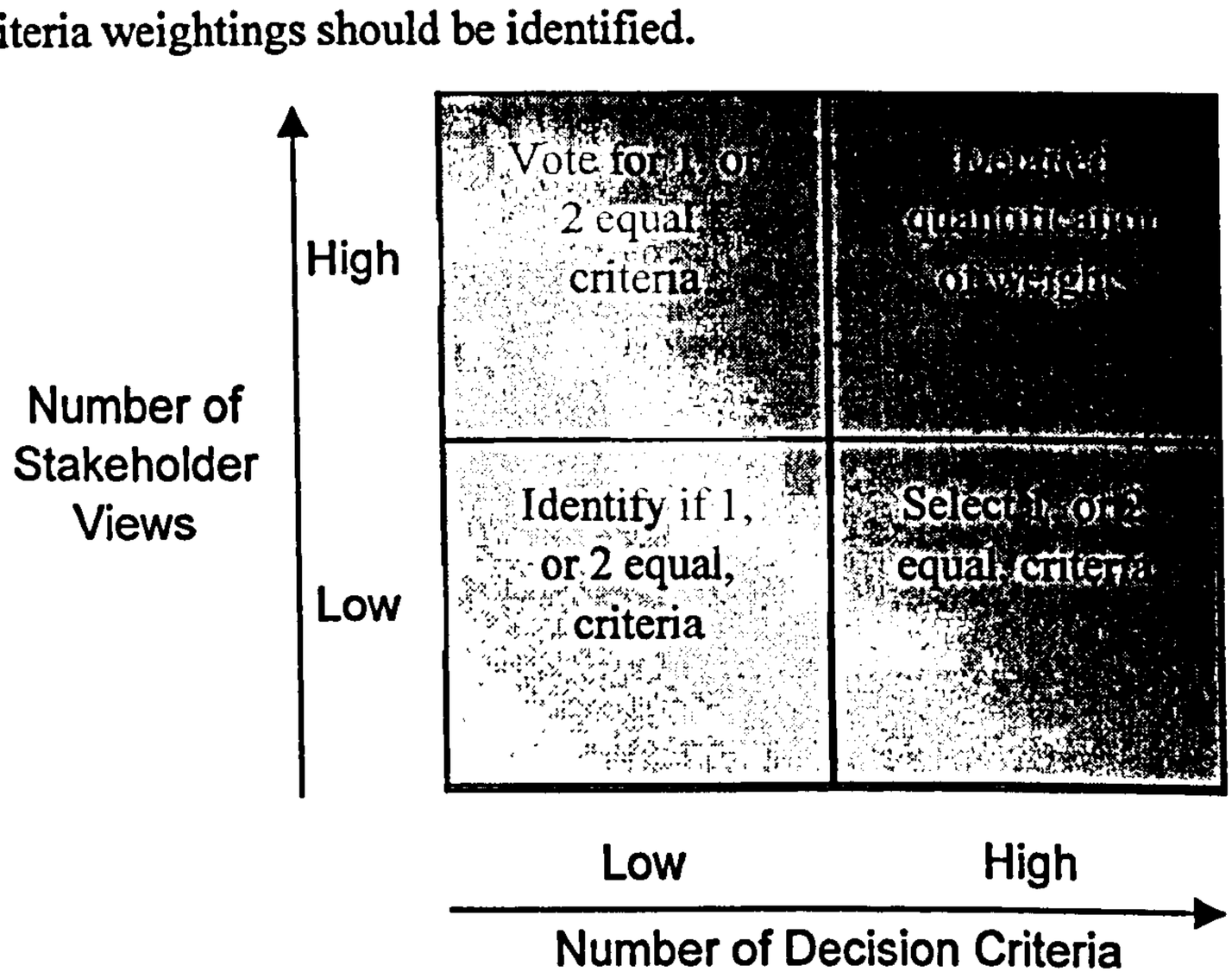
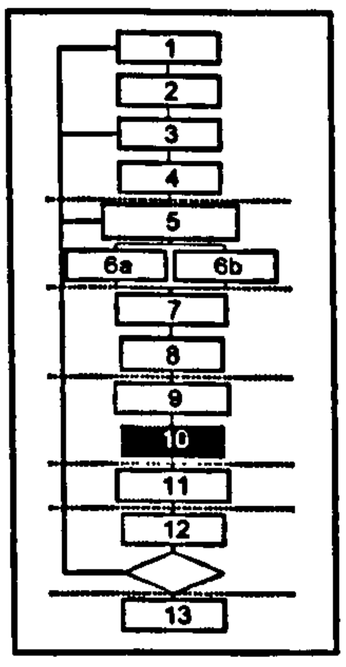


Figure 38 Matrix for identifying the relative importance of decision criteria

11.11 Identify Preferences for each Outcome

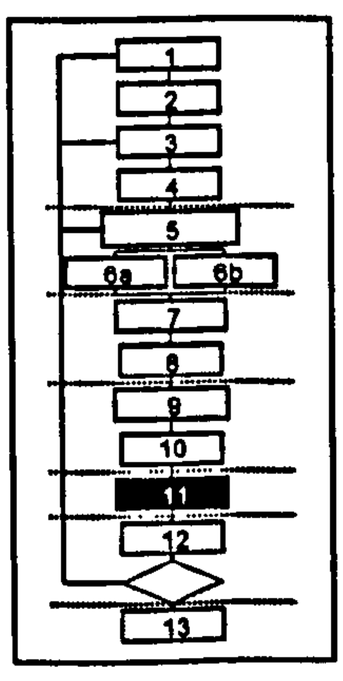


The identification of preferences for each outcome can be a very complex stage in the decision process. Consequently it is often left out. It is important for the decision-maker to consider whether there is a preference in the values of the outcomes of the decision. For example, whether there is a preference for a low probability of a high consequence or a high probability of a low consequence. Alternatively, there may be more of a preference for a low risk to a higher risk or a lower cost to a higher cost. Such an assessment was only carried out in one of the case studies. In case study 4 (prioritising bridge strengthening works), because all criteria values were transferred to a non-dimensional scale, a non-linear relationship was derived for value and risk, although all other criteria were mapped onto linear scales. For all other case studies, the decision-makers were not interested in identifying value preferences, except in some cases specifying minimum or maximum acceptance levels.

In case study 5 (review of risk-based decision-making in APA) there was no evidence of any quantification of preferences. However, there was evidence of subconscious preferences being introduced by the decision maker, for example preferences for minimising short term costs rather than long term costs and minimising short term risks rather than long term risks.

The value of the decision-making process is enhanced by raising awareness in both the decision-maker and the stakeholders of any subconscious preferences and biases. This allows them to be identified and evaluated. If they are significant then this can be quantified in the formulation and assessment of the decision problem. The tools for quantifying these preferences were described in Chapter 4 and were found to be tedious, difficult and time consuming. These methods will help in the decision-making process, but only if the decision maker is committed to this level of quantification. He has, therefore, to be convinced that the result will be worth the effort. This is a very important area for further development. The possibility of developing simpler, more efficient methods should be established and if possible, further development work should be carried out to support this stage of the process more effectively.

11.12 Choose Best Alternative based on Expected Utility



It is not always necessary to evaluate the decisions in terms of a non-dimensional utility, for example, it need not be done if the decision is to be made on one main criterion. In case study 1 (feasibility of re-using subsea facilities in new developments) the decision was based on minimising the expected cost (i.e. the sum of the probabilities of failure and the costs of failure). Similarly, in case study 3 (planning pipeline repair & replacement schedules), the decision was based on minimising the risk of failure. In case study 4 (prioritising bridge strengthening works), because of the multiple criteria on which the decision was evaluated, in was necessary to maximise the utility of each alternative.

In case study 2 (developing a maintenance strategy for viaduct crossbeams), however, due to the complications of scheduling and deterioration, a more complex decision rationale had to be adopted.

The decisions which were investigated in case study 5 (review of risk-based decision-making in APA) were often based more on preferences and perceptions of cost and safety risk than any clear optimisation of calculated values. Despite carrying out detailed calculations of costs and risks in some cases, these values were sometimes ignored when it came to the final decision, as the risks, where possible, were transferred back to the operator. Therefore, the best decision, at least from the operator's perspective was not always made. Figure 39 presents a matrix to help the decision maker identify the most appropriate basis for the final decision depending on the number of decision criteria and the complexity of the decision problem.

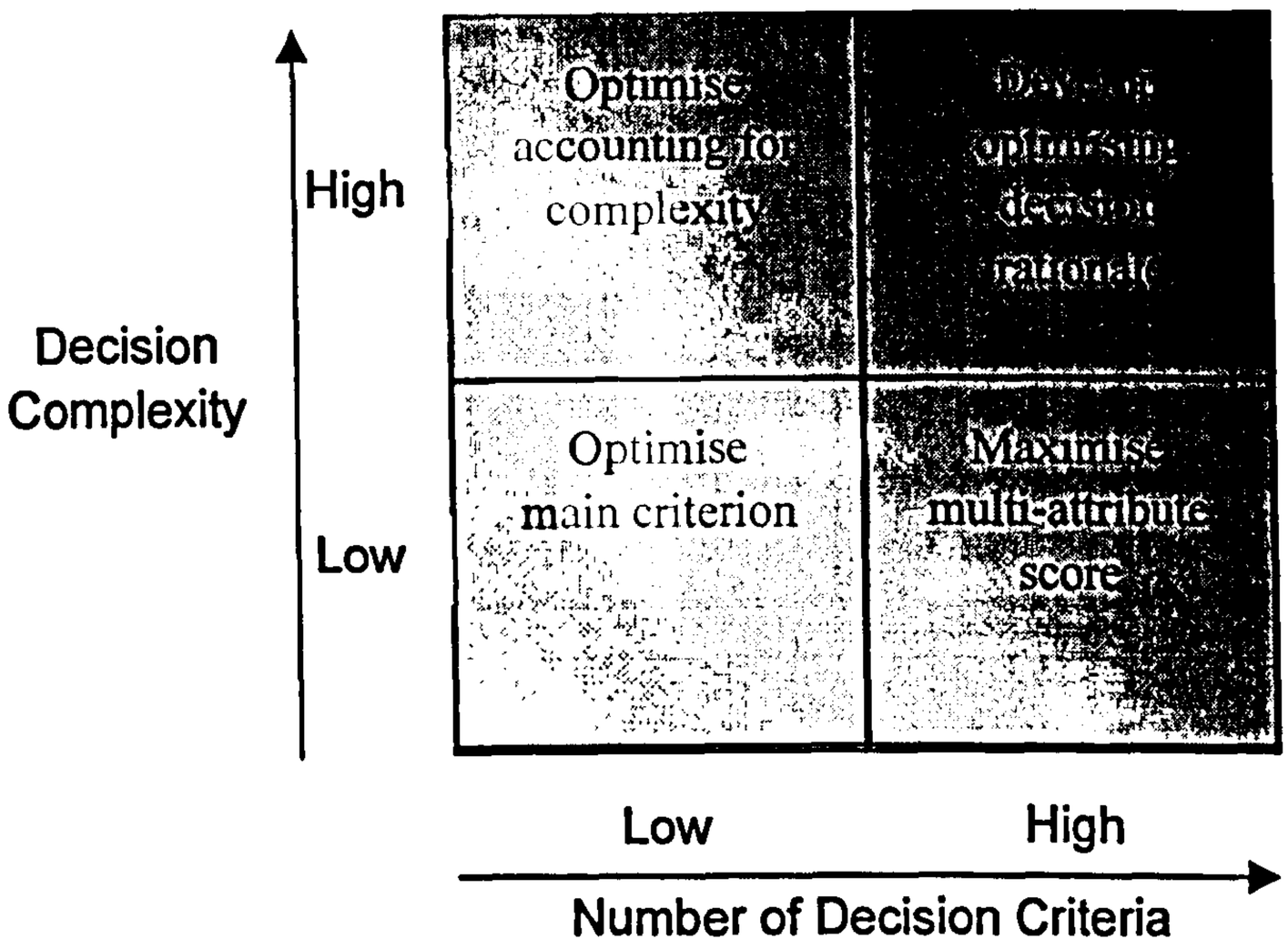
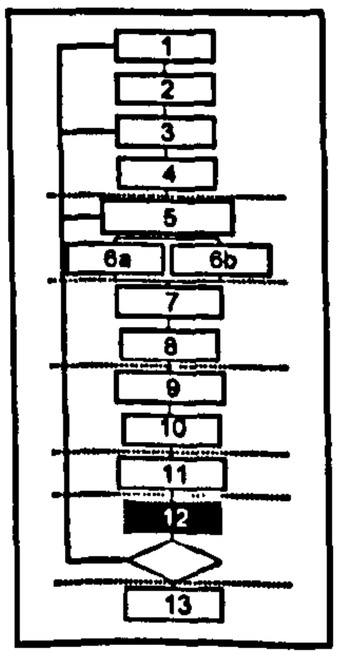


Figure 39 Matrix for the method of selection of the best alternative

11.13 Conduct Sensitivity Analysis



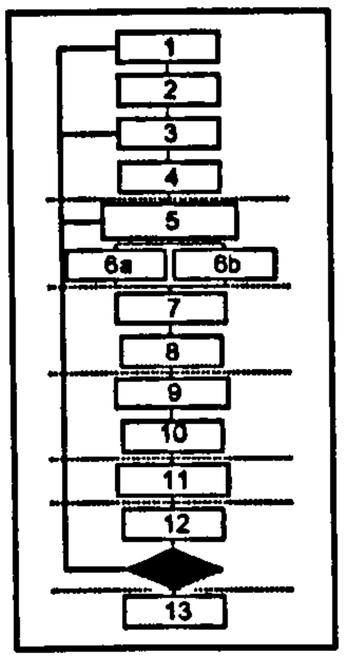
Due to the uncertainties inherent in all decision-making, it is necessary to establish the effects of the assumptions and of parameter uncertainties on the selected solution. In case study 1 (feasibility of re-using subsea facilities in new developments), the uncertainties were determined subjectively based on expert opinion; the sensitivity analysis analysed the extremes of the experts estimates to assess whether the selected alternative would change. In case studies 2 to 4, however, the probabilities were defined more objectively therefore different sensitivities were important. In case studies 2 (developing a maintenance strategy for viaduct crossbeams) and 3 (planning pipeline repair & replacement schedules) the decision was based mainly on the probability of failure, therefore the sensitivity of the selected option to the uncertainties in the probabilities was of greatest importance. In case study 4 (prioritising bridge

strengthening works) the decision was based on the weighted criteria scores, therefore the sensitivity of the selected option to the criteria weights needed to be determined. Despite the importance of sensitivity analysis, it was not performed in every case study. In some cases the client insisted on making the decision on the first pass results. It is concluded that there is a need for decision-makers to be educated about the benefits of sensitivity analysis and the dangers of not carrying it out.

Case study 5 (review of risk-based decision-making in APA) revealed that sensitivity analysis was not used in any of the decisions investigated. This meant that it was not possible to demonstrate any confidence in the final decisions. It seems common for decision-makers, once they have made a decision, to stick with it and move straight into implementation. This can be done without any checks to ensure that the assumptions and estimates either were correct, or did not affect the final decision in any way. This can lead to a poor decision. However, even where the decision is appropriate, the lack of robust evidence to demonstrate confidence in the decision can adversely affect motivation during the implementation stage.

Sensitivity analysis does therefore make a significant contribution to the decision process. Even if only at a qualitative level. It helps to avoid poor decisions and by building confidence in good decisions produces motivation during implementation.

11.14 Conduct Further Analysis if Required

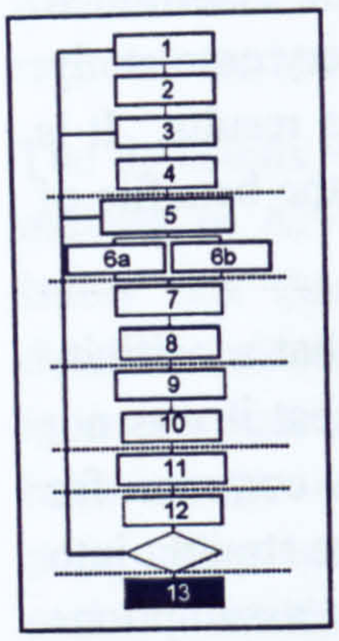


Carrying out further analysis is perceived to be expensive and is therefore often neglected. As experience from case studies 1 to 4 shows, that, despite recommendations being made for additional data gathering and re-analysis of the decision, this recommendation was not put into practice, in any of the cases. It seems that the application of the risk-based decision process to support the decision-making in these four cases was so revolutionary and made the decision-making process appear to be so logical that the decision makers had complete confidence in the recommended solutions. They could perceive no additional benefit that might be derived from additional analysis.

In case study 5 (review of risk-based decision-making in APA), since none of the decisions involved any sensitivity analysis, no re-analysis using either revised data or assumptions or additional data was performed.

If the decision facilitator was convinced of the benefit of carrying out additional analysis, then they should provide a clear quantitative demonstration of the benefit of using additional data and analysis to improve the problem solution. In cases where there is little difference between two alternative solutions, then such a demonstration may be straightforward to achieve. However, if one option is clearly better than any other, then it is likely to be difficult to convince a decision-maker to pay more for information, which is unlikely to change the decision.

11.15 Implement the Chosen Decision



Evaluation of case studies 1 to 4 shows that in all four cases the decision recommended by the decision facilitator as a result of using the risk-based decision process was accepted by the decision-maker and subsequently implemented. The risk-based decision process had made the decision-making transparent to all stakeholders who could then understand and accept the reasons for the selected options. This promoted ownership of the decisions, which in turn motivated all parties to contribute to the implementation of the solution.

In case study 5 (review of risk-based decision-making in APA) significant evidence was found for decisions being made without consensus between stakeholders and even with clear conflicts remaining unresolved. This led to solutions being implemented without agreement and support and even encouraged a culture of blame when the solutions were found not to be the best for all parties. The other significant problem found in case study 5 was the lack of feedback and control during the implementation of the decision, which led to risks developing out of control and therefore decision objectives not being met. For this reason, it was considered that the feedback loop should be incorporated into the decision process.

The implementation stage therefore is a significant step in the risk-based decision-making process. It is obviously important to ensure that the decision is acted on and not left as a document on the shelf. However, it is also important that the decision is implemented in accordance with the consensus of all stakeholders and monitored and controlled to ensure that risks are controlled and that the consensus decision objectives are fulfilled. This plays a very significant role in ensuring a successful decision.

11.16 Decision Facilitation

One consideration in the use of the decision process, which has not yet been addressed, is the use of a facilitator in the decision process. Each of the decisions described in the first four case studies was facilitated to varying degrees by myself as a third party consultant. This had a number of benefits, each of which made the decision-making more thorough, rational and unbiased. Firstly, being separated from the decision-maker and any of the stakeholders meant that the decision problem could be viewed independently and without bias. It also meant that the decision facilitator saw the problem as part of the bigger picture, above the prejudices and possible blinkered experiences of the decision-maker. This enabled increased creativity and lateral thinking in terms of identifying stakeholders, alternative solutions and risks.

Another key role and benefit of the third party facilitator in decision-making is as an independent judge in conflict resolution. When stakeholders hold strong but conflicting views about the way the decision is made and about the preferred final decision, the facilitator can arbitrate between opposing sides. This can help to bring about a better understanding between parties and build a consensus between them. The symptoms of conflict can be identified very early on in the decision process. These include poor

communication between stakeholders, hostility and jealousy between stakeholder groups, interpersonal friction and low morale. Without conflict resolution through a third party facilitator, stakeholders could adversely affect the decision by controlling or distorting information by using informal communication and negotiation channels and by controlling rewards. The facilitator, being independent of the problem, has the best opportunity to turn the conflict into a state of collaboration or fruitful argument (the fruitful discussion of differences) [161]. Through trying to understand the reasons for the conflict, the facilitator can neutrally promote the agreed goals of the decision in order to overcome the disagreements between stakeholder groups. This was experienced through consensus building as in case study 4.

Mintzberg [162] developed a set of ten roles, which, he proposed, were involved in the execution of management. These roles are shown in Figure 40 below.

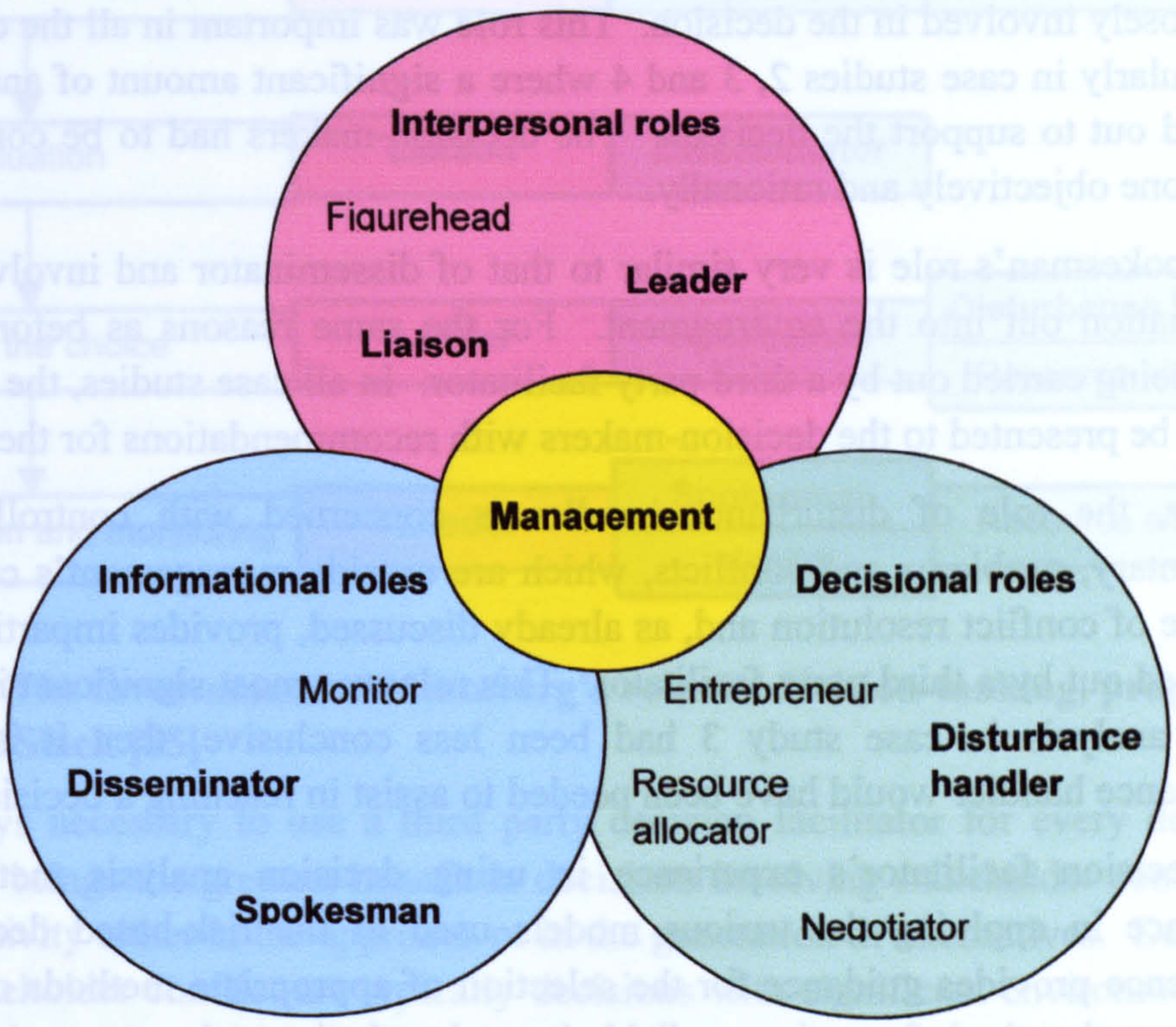


Figure 40 Ten management roles proposed by Mintzberg [162]

Cooke and Slack [85] took this further and suggested that, since the key role of management is decision-making, these ten roles should play a part in the decision-making process. Figure 41 shows the way in which Cooke and Slack mapped these roles against the generic decision process. I believe that in order to maximise the effectiveness of the decision-making, five of these roles can be best performed by a third party facilitator. These five roles are highlighted in the figure (bold text).

The role of leader provides direction, guidance and motivation to the decision group, ensuring that the decision process is followed and committed to by all in the decision group. A third party facilitator here helps to overcome cynicism and mistrust at an early stage in this process. Although this role was evident in all four case studies, it was of

particular significance in case studies 1 and 4 where stakeholders had to be motivated to participate in rigorous evaluations.

The role of liaison is to build and maintain links and contacts with groups and individuals outside the decision group. This role of stakeholder liaison also benefits from the independence and impartiality of a third party facilitator. This role was evident to some extent in all four case studies. It was crucial to the success of case study 4 where the stakeholders not only had to be consulted but also had to be reassured that their views were being represented.

The role of the disseminator is to pass information into the organisation from outside and to pass on information generated by the decision group. If this role is carried out by a third party facilitator then, there can be confidence that information is communicated and represented fairly and honestly without bias and prejudice that can come from being too closely involved in the decision. This role was important in all the case studies, but particularly in case studies 2, 3 and 4 where a significant amount of analysis had to be carried out to support the decision. The decision-makers had to be confident that this was done objectively and rationally.

The spokesman's role is very similar to that of disseminator and involves transmitting information out into the environment. For the same reasons as before, this benefits from being carried out by a third party facilitator. In all case studies, the analysis results had to be presented to the decision-makers with recommendations for the best decision.

Finally, the role of disturbance handler is concerned with controlling the, often involuntary, problems and conflicts, which are outside management's control. This is the role of conflict resolution and, as already discussed, provides impartiality and order if carried out by a third party facilitator. This role was most significant in case study 4. If the analysis in case study 3 had been less conclusive, then it is likely that a disturbance handler would have been needed to assist in reaching a decision.

The decision facilitator's experience in using decision analysis methods provides assistance in applying the various models used in the risk-based decision process. Experience provides guidance for the selection of appropriate methods of analysis and can ensure that the information available is used to the best advantage. An experienced, independent decision facilitator also brings confidence to the decision-making, both the primary decision-maker and for the other stakeholders. Through his experience, the decision facilitator, can impart confidence in the process and its application to the problem, while through his independent unbiased view he can provide confidence in the fairness and rationality of the decision process. This encourages ownership and support for the decision and motivation for its implementation.

The traditional role of the facilitator is to ensure the appropriate application of the process. When facilitating this decision process, his role is much richer. The facilitator must be sensitive to the issues and complexities of the decision problem. There must also be a flexible balance between the 5 key roles and in the application of the decision tools at each stage, even to the extent of intervening in the evaluations to ensure all

views are represented. If the right balance of roles is not achieved, for example if the leader role dominates, then a wrong or insensitive decision may be made.

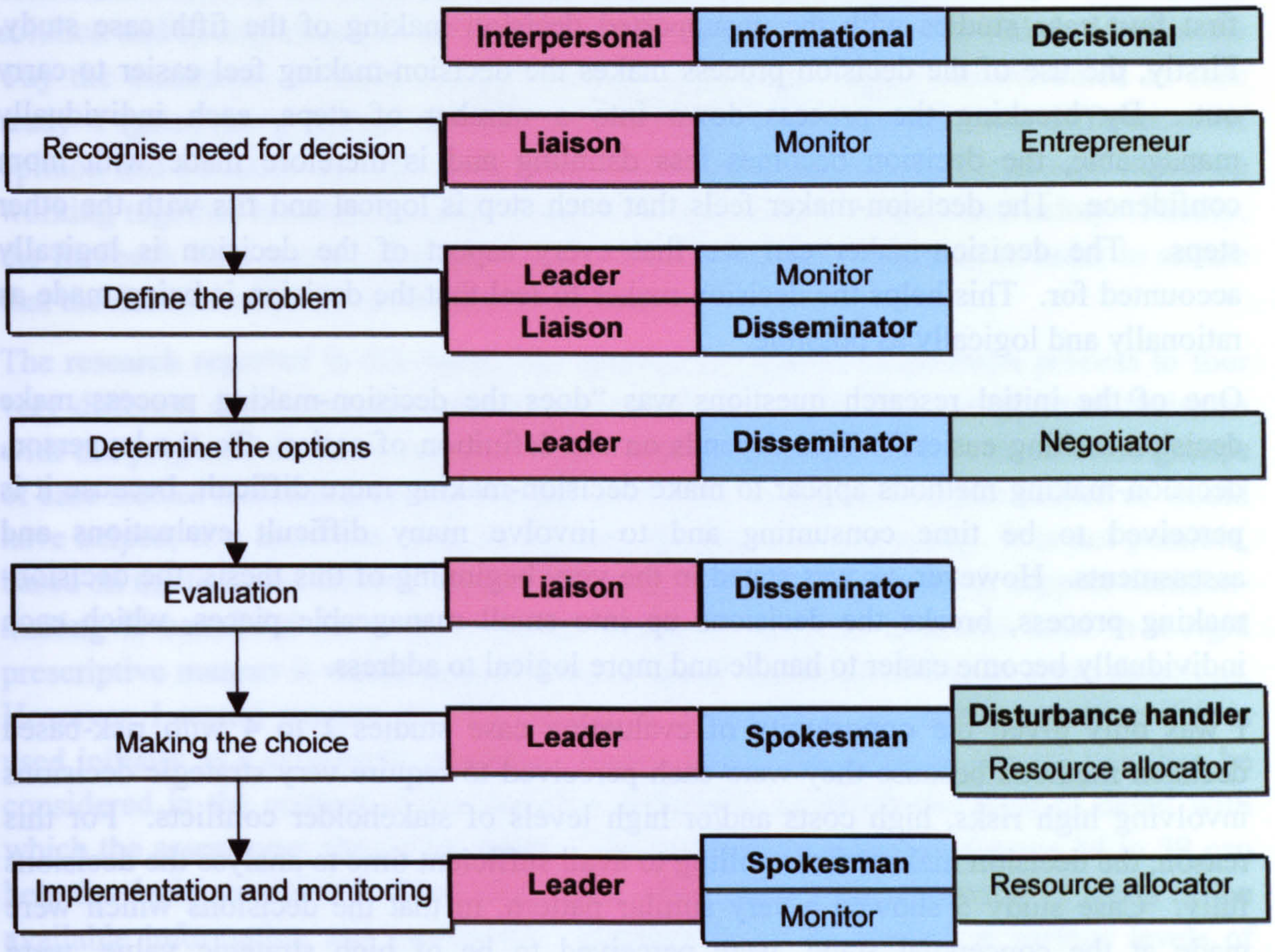


Figure 41 The involvement of Mintzberg's roles in decision-making, proposed by Cooke and Slack [85]

It is not always necessary to use a third party decision facilitator for every decision. The facilitator brings the greatest benefit in decisions involving stakeholder conflict, or requiring creativity either in the approach or in the generation of alternatives. Decisions involving stakeholder conflict are typically decisions with significant environmental or political consequences, such as the decisions considered in case studies 3 and 4. Case study 2 is a good example of a decision requiring creativity in the way it was solved. Another class of decision that could benefit from a third party facilitator is those that involve a significant amount of subjective evaluation. Subjective evaluations, by their very nature, involve biases and perceptions. These can affect the decision that is made. By using a third party facilitator the stakeholders can be guided in their subjective evaluations in order to ensure that the effect of biases and perceptions is kept to a minimum. Case study 1 was an example of this type of decision. Decisions involving minimal stakeholder influence, based predominantly on cost and safety issues do not need a third party facilitator and can be managed directly by the decision maker. However, the decision-maker should have an understanding of and experience in decision analysis and risk assessment methods to be able to make the decision without external support.

11.17 General Discussion

A number of points can be made by comparing the supported decision making of the first four case studies with the unsupported decision making of the fifth case study. Firstly, the use of the decision process makes the decision-making feel easier to carry out. By breaking the process down into a number of steps, each individually manageable, the decision becomes less daunting and is therefore made with more confidence. The decision-maker feels that each step is logical and fits with the other steps. The decision-maker can see that every aspect of the decision is logically accounted for. This helps the decision-maker to feel that the decision is being made as rationally and logically as possible.

One of the initial research questions was "does the decision-making process make decision-making easier?" This depends on the definition of easier. To the layperson, decision-making methods appear to make decision-making more difficult, because it is perceived to be time consuming and to involve many difficult evaluations and assessments. However, as was stated in the very beginning of this thesis, the decision-making process, breaks the decisions up into small manageable pieces, which each individually become easier to handle and more logical to address.

I was only given the opportunity of evaluating case studies 1 to 4 with risk-based decision methods because they were each perceived to require very strategic decisions involving high risks, high costs and/or high levels of stakeholder conflicts. For this reason, the decision makers were willing to avail sufficient time to analyse the decisions fully. Case study 5 showed a very similar pattern, in that the decisions which were made at the conceptual stage, were perceived to be of high strategic value, were allocated more time in which to identify and evaluate alternatives than was the case for the detailed design decisions. This does not mean that the risk-based decision process is only appropriate for high level decisions, although it obviously does bring significant benefit to them. In lower level decisions, when used as a check list or a diagnostic, the risk-based decision process can ensure that all decisions are considered and evaluated rationally and at a level of detail appropriate to the given situation.

This will help decision-making overall become more rational, but does it help make better decisions? The answer to this question depends on the definition of a good decision. Is a good decision a decision with a good outcome, irrespective of how it was made? Is it a decision made in a thorough and rational manner irrespective of the outcome? Alternatively, is it a decision made in a thorough and rational manner with a good outcome? I would suggest that since decisions are made under uncertainty, it is not right to grade the quality of a decision on its eventual outcome. In my view, a decision should be classified as a good decision if it has been made in a thorough and logical manner taking account of all factors, all preferences and all uncertainties. In which case, the risk-based decision process does help to promote better decisions.

Not only does the risk-based decision process help to make better decisions but it also helps in the implementation of the decision. Through the logical and thorough process, a clear audit trail is built up allowing the whole process to be inspected and assessed

later. Furthermore, the integration of stakeholder views into the decision process creates ownership from all parties throughout the decision process. This promotes consensus building and motivates all parties both to work together to find a workable solution and to implement it. It also encourages accountability to the stakeholders in the way the consensus decision is implemented. This was clearly demonstrated in case study 4 (prioritising bridge strengthening works), which showed how differences of opinion and political conflicts were resolved such that all stakeholder groups ended up working together towards the same goals of overall cost efficiency and safety. Finally, the feedback loop ensures that all risks are monitored and controlled in order to ensure that the decision objectives continue to be met.

The research reported in this thesis has applied the risk-based decision process to four very different decision scenarios and compared thirteen further unsupported decisions with the proposed decision process. The experience gained from both of these groups of case studies has indicated that the risk-based decision process either helped or would have helped, if it had been used, in the way the decision was made. It is not possible, based on the five case studies, to say that using the decision process to support decision-making is beneficial for every decision problem. In fact, if it was used in a rigid prescriptive manner it would probably hinder good decision-making in some situations. However, I would suggest that the process is a support to all decision-making if it is used initially as a systematic checklist. Each stage of the decision process can then be considered in the context of the decision at hand to establish the level of detail with which the assessment should be made. The matrices presented in figures 34 to 39 can help the decision-maker in these stages; the other stages being evaluated in terms of the available information and experience. Because it can be applied at various levels of detail and allows for choices of methods within its different stages, the proposed decision process is inherently flexible and is suitable for application to a very wide range of problems. The strength of the process lies in its ability to help the decision-maker identify and consider all factors which affect the decision and then to provide a range of models to evaluate the more complex stages of the process.

The framework proposed by UKOOA [123], reviewed in Chapter 4 divided all possible decision scenarios into 3 general types, based on a set of common drivers and issues, and recommended basing the different decisions types on different types of assessments and information (see Figure 11). For example standard, "run of the mill", low risk decisions, with minimal economic or stakeholder implications, should be based predominantly on codes and standards, good practice and engineering judgement. Decisions involving business or life cycle risks, some uncertainty or deviation from standard practice and some significant economic implications should be based on the same three methods supplemented by cost benefit analysis, quantitative risk assessment and an understanding of company values. Finally, very novel or challenging decisions involving strong stakeholder views, significant risks, uncertainties, economic implications and a lowering of safety standards should be based on company and societal values with input from cost benefit analysis or quantitative risk assessment.

The UKOOA approach therefore implies that it is not appropriate to use risk-based decision-making in everyday decisions and hence that it is not necessary to calculate risks or stakeholder values. However, this could lead to risks being accidentally overlooked or accidentally introduced, by assuming that the decision is similar to many previous decisions based on code assessments. There may, in fact, be subtle differences which mean the code is not directly applicable, or that the context of the decision introduces uncertainties and risks. Codes may also incorporate hidden assumptions, which can mean that a slightly innovative design may not fit the code or be suitable to be judged against the code. These issues have the potential to introduce additional risks, which may remain hidden, without prompting from a formalised decision process.

I therefore disagree with UKOOA's view and suggest that risk is involved in every decision, but that it is better understood in some decisions than others. In common with the UKOOA framework, the decision process recommended in this thesis suggests that it may not always be necessary to carry out a QRA or evaluate stakeholder views. However, rather than trying to band all decisions into three general types, the proposed risk-based decision process takes the decision maker through the decision one step at a time, initially as a checklist to ensure that the decision maker considers every aspect of the decision at hand. This allows the decision-maker to identify the relevance, benefit or importance to calculate risk, evaluate stakeholder views, use multiple criteria and quantify preferences, to the decision at hand. Then, through the applicability matrices presented in Figures 34 to 39, it helps the decision-maker to achieve a decision, with the support of the recommended models appropriate to the context of the problem.

If all decisions could be easily grouped into the three general decision types proposed by UKOOA's framework, then both UKOOA's framework and my proposed decision process would look quite similar, as shown in figure 42. This figure also helps clarify the level of effort required by the decision process for different types of decisions based on the applicability matrices presented previously. However, decision problems do not all fall neatly into the three general types, but may have characteristics from any type. The risk-based decision process recommended by my research is therefore less prescriptive and more flexible than the framework presented by UKOOA, since it allows each decision to be evaluated independently of anything else.

The risk-based decision process proposed in this research is able to support all decision-making by ensuring that all factors are accounted for explicitly rather than assuming that some factors can be ignored as would be the case with UKOOA's framework. This therefore provides a full audit trail with which to justify the decision at a later stage to prove that all factors were considered explicit. The step by step process and resulting audit trail gives confidence to decision makers at every level in the corporate hierarchy and helps more junior decision-makers justify their decisions to their seniors.

The additional benefit of the work described in this thesis, over the framework proposed by UKOOA, is that this thesis has identified, developed and applied a range of decision tools and models to support each stage of the decision process.

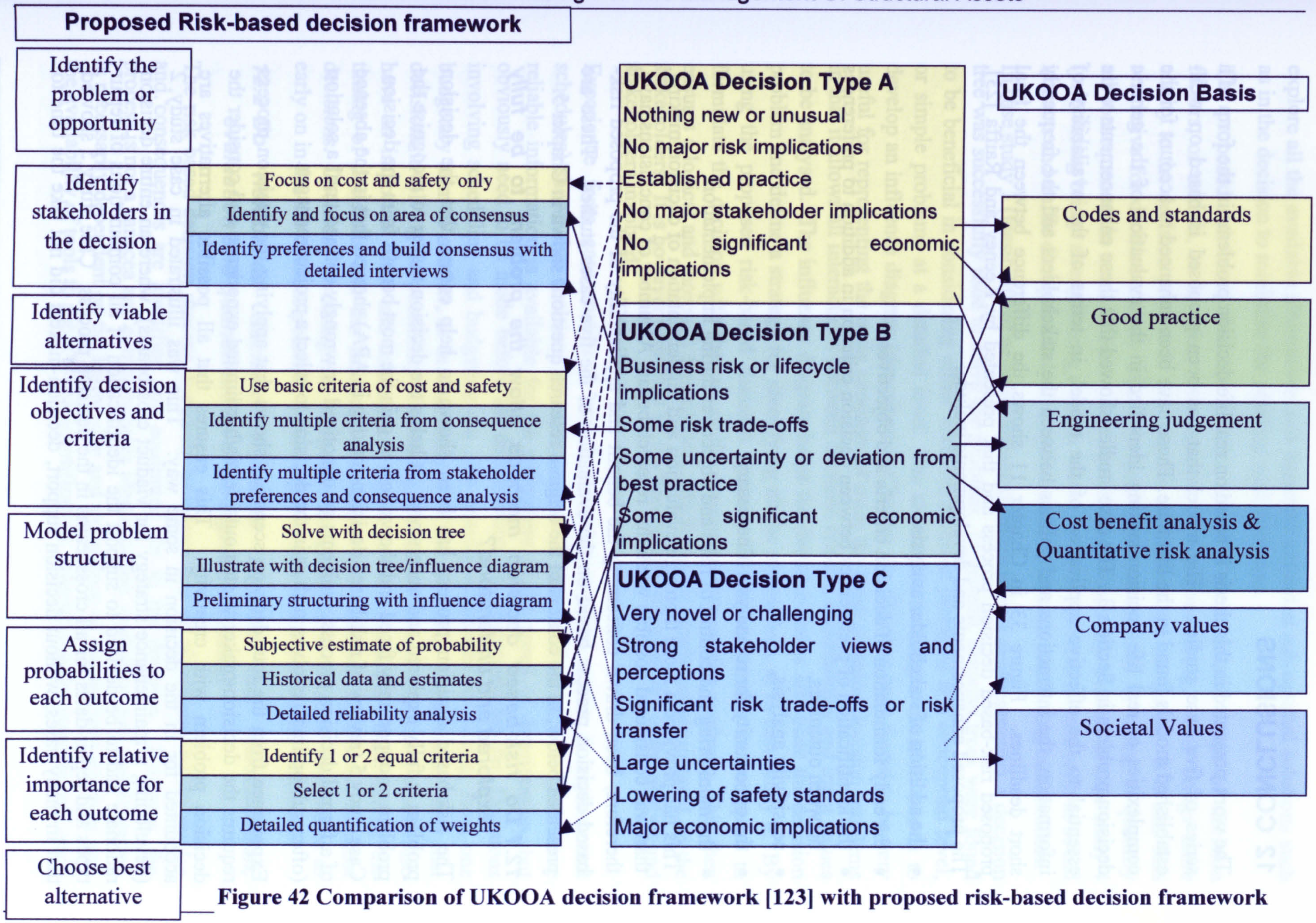


Figure 42 Comparison of UKOOA decision framework [123] with proposed risk-based decision framework

12 CONCLUSIONS

The work presented in this thesis is based on real life decision problems in the form of a series of five case studies. The model that has been proposed is based on well-established models found in the literature. These have been enhanced to account for the complexities of real life decision-making identified in the evaluation of the generic decision problem in Section 3. The case studies showed that these enhancements were essential to the effective application of the model, in terms of the availability of information, the interactions and politics between the stakeholders and the frequently short deadlines. Figure 33 in Chapter 11 shows the difference between the final proposed risk-based decision process and that presented by Keeney and Raiffa [23]. The proposed enhancements and developments include:

- the addition of stakeholder analysis,
- the early formulation of decision criteria and objectives,
- the identification of preferences between decision criterion in addition to preferences between outcomes,
- sensitivity analysis,
- the opportunity for re-analysis if necessary,
- the monitoring and control of risks and objectives during implementation.

This has provided a more thorough evaluation and implementation of decision-making, than was considered possible when this research began. A number of conclusions have, therefore, been drawn concerning the benefit and applicability of the proposed risk-based decision process based on the evaluation of the five cases studies. These are presented below, in the context of the original research questions shown in Chapter 5.

12.1 Do risk-based decision methods allow the problem to be fully explored and understood?

The risk-based decision process has been shown to help ensure that the decision problem is fully explored and understood. It helps the decision-maker to recognise the problem or opportunity faced and shows how to gain the most benefit from the decision. Case study 5 (review of risk-based decision-making in APA) showed that in the absence of a formal decision process, problems go unnoticed or wrongly defined until a solution (often sub-optimal) evolves such as in the decision to select a project manager.

Experience from the four decision scenarios shows that applying the decision process requires the decision-maker to step outside his/her limited experience and consider the decision problem with creativity. This ensures that all possible alternatives are accounted for in the decision in some way. This was illustrated in case study 2 (developing a maintenance strategy for viaduct crossbeams), where an entire decision rationale had to be devised to support the identification of all combinations of repair types and repair dates for all crossbeams in the decision process. Case study 5 showed that in many cases, without decision support, decision-makers did not take the time to

explore all the available alternatives and therefore arrived at sub-optimal solutions such as in the decision to minimise the pipeline wall thickness.

The proposed risk-based decision process allows a more diverse range of decision factors, or criteria, to be taken into account in decision-making. This brings more clarity to the decision process in the way the alternatives are compared. It is also less restrictive for decision-makers who were previously constrained by trying to quantify all consequences in terms of cost. This benefit was particularly evident in case study 4 (prioritising bridge strengthening works), where the use of diverse criteria such as social impacts and traffic disruption helped build consensus between conflicting stakeholders.

In case study 1 (feasibility of re-using subsea facilities in new developments), a decision tree was successfully used to solve the problem. In general, decision trees were found to be beneficial in considering either complex decision problems at a conceptual level, or simple problems at a detailed level. The alternative to using a decision tree is to develop an influence diagram (described in Chapter 4). This has been found to be very useful for representing the main concepts of even the most complex decision problems in that it allows all interactions between decision criteria, uncertainties and input values to be analysed. The influence diagram helps the decision-maker articulate the decision problem and define a strategy for identifying all the alternatives, as in case study 4. By using the proposed risk-based decision process, the decision-maker is prompted to formulate the decision with the use of the appropriate structuring method. This then ensures a logical and thorough formulation, which can be clearly communicated, to the stakeholders. It is however restricted by the knowledge and creativity of the analyst and stakeholders involved.

Experience from case studies 2 and 3 (planning pipeline repair & replacement schedules) shows that decisions involving structural deterioration are best made once reliable information is available for the estimation of the speed of deterioration, but obviously need to be made before the deterioration has progressed too far. Decisions involving scheduling and budgeting are also heavily influenced by timing, from one budgetary term to another, as in case study 4. Case studies 2, 3 and 4 also show that decisions involving the possibility of updating data based on new inspection results also have an important time and information aspect to be considered. Establishing the timing of decisions and the information required are therefore significant in most decisions. Decisions involving risk mitigation design are most effective when taken as early on in the life cycle as possible, before other design factors have been finalised.

12.2 Do risk-based decision methods support the identification, evaluation and quantification of all significant risks?

The risk based decision process does help to ensure that all significant failure modes and consequences are identified and accounted for in the decision. However, the process is not a panacea and comprehensive identification, evaluation and quantification is necessarily dependent on the knowledge and experience of the analysts involved and the availability of tools to support risk identification. Identifying the possible outcomes

for each alternative allows the right emphasis to be placed on either mitigating against failure or providing contingency in the case of failure.

The process supports the quantification of risk to the level of detail appropriate to the context of the decision problem. For example, it was considered adequate in case study 4 to evaluate the risks based on a simplified risk scoring system rather than carrying out a detailed structural reliability analysis of every bridge under consideration. The risk-based decision process, in involving all stakeholders throughout each stage of the decision, ensured that the consequences and probabilities of all possible outcomes were evaluated in the interest of all stakeholders. This provided a full understanding by all parties and helped to build consensus in the decision. This was particularly true in case studies 1 and 4, where different risks were identified to affect different stakeholders.

In case studies 2 and 3, due to the inherent uncertainties, it was found necessary to establish the effect of the assumptions and parameter uncertainties on the selected solution. Sensitivity analysis was therefore an important stage, even at a qualitative level, to build confidence and motivation for the implementation of the decision.

In one of the decisions in case study 1 there was very little difference between two alternative solutions, therefore it was recommended that further analysis be carried out. However, conducting further analysis can be expensive and as the decisions were made at a conceptual level they were not taken any further. It is therefore necessary to quantitatively evaluate the benefit of additional data and analysis to improve the problem solution before this is recommended to the decision-maker.

12.3 Do risk-based decision methods support the identification and agreement of a preferred course of action?

The risk-based decision process has been shown to support the identification and agreement of a preferred course of action. However, the detail involved in identifying and evaluating stakeholder preferences in the decision has been found to depend on the time within the life cycle. It also depends on the number and strength of conflicting opinions affecting the decision. Generally, these "softer" decision-making issues are only considered when there is time and motivation to consider them, such as at the conceptual design stage or when considerable stakeholder conflict needs to be resolved, as in case studies 1 and 4. The use of the risk-based decision process provided a prompt for stakeholder issues to be considered and allowed an evaluation to be made of whether more detailed assessment of influences and preferences should be undertaken. This helped the overall best decision to be made to suit all parties involved. Decisions made without the support of the decision process did not recognise stakeholder issues, and therefore took no account of the sometimes subtle effect of stakeholder preferences and biases. This was found to be true in many of the decisions evaluated as part of case study 5, especially when objectives differed between contractors and operators.

It is not always necessary to quantify specific weightings for each decision criteria, especially when only one or two criteria are considered. In these cases, gaining consensus from the stakeholders concerning the dominant criterion, was found to be a

useful clarification of the decision process, such as in case study 3 (planning pipeline repair & replacement schedules), where safety was considered the dominating criterion. The risk-based decision process causes the selection of decision criteria and the quantification of the relative importances of the criteria to be carried out systematically in a way that is auditable after the event. In case study 4 (prioritising bridge strengthening works) a thorough evaluation was considered imperative to build consensus and understanding between all stakeholder groups, and to ensure that all were satisfied that the funds were allocated fairly amongst their requirements.

The identification of preferences for each outcome can be a very complex stage in the decision process and therefore is frequently not carried out. It is important for the decision-maker to consider whether there are preferences concerning the values of the outcomes of the decision. This allows them to be identified, evaluated and if significant quantified in the decision problem formulation and assessment. The only case study in which this was carried out was case study 4 (prioritising bridge strengthening works), again because of the need to satisfy all stakeholders that all risks were considered fairly.

12.4 Can risk-based decision methods make engineering decision-making easier?

The decision-making process makes engineering decision-making easier by breaking the decisions up into small manageable sections, each of which when considered individually become easier to handle and more logical to address. The decision process provides a checklist to help the decision maker consider all factors pertinent to the decision. The applicability matrices guide the decision-maker to understand the best approach to use to solve the decision at each stage. The decision then becomes less daunting and hence is made with more confidence. Each step forms a logical process and each step fits together with the rest. The decision-maker can then see that every aspect of the decision is accounted for in a logical manner. The use of the decision process has, therefore, been shown to make the decision-making easier to carry out, however, it does not necessarily make decision-making quicker to carry out.

12.5 Can risk-based decision methods help make more rational engineering decisions?

The risk-based decision process has been shown to make decision-making more rational by supporting the identification of all factors influencing the decision. It also ensures that the most suitable models are used to evaluate each relevant factor in terms of the required decision. The alternatives are therefore fully quantified, which means that the decision-maker can compare the alternatives to select the one that most fully meets the decision objectives. This detailed evaluation process helps the decision-maker to make the decision as rationally and as logically as possible.

12.6 Can risk-based decision methods help make engineering decisions more auditable?

The systematic risk-based decision process encourages consideration of everything important to the decision. When this process is documented at each stage to explain

what was considered, why and what methods of evaluation were adopted, a thorough history of how the decision was made and justification for the adopted solution is provided. Such a document is then available for future consultation, to prove the rationality of the decision that was made. This is a very thorough audit trail, which can be kept for as long as necessary to provide the explanation and justification for the decision, it can also serve as a basis for learning lessons in the future.

12.7 Can risk-based decision methods help build consensus and ownership in engineering decisions?

The risk-based decision process makes the decision-making transparent to all stakeholders who can then understand and accept the reasons for the selected options. The integration of stakeholder views into the decision process creates ownership from all parties throughout the decision process. This promotes consensus and motivates all parties to work together to find a workable solution and to implement it. It also encourages accountability in the way the consensus decision is implemented.

12.8 When is it appropriate to use risk-based decision methods in engineering decision-making?

The experience gained from applying the decision process and comparing it against unsupported decisions has indicated that the risk-based decision process either helped, or would have helped if it had been used, in all decisions studied. If the risk-based decision process was used in an overly prescriptive manner, it might in some situations hinder good decision-making and the time required would often be prohibitive. However, the process is a support to all decision-making if it is used initially as a systematic checklist. The matrices presented in Figures 34 to 39 help the decision-maker to establish the level of detail required. The various levels of detail and the choices of methods at the different stages of the decision process bring a great deal of flexibility to the process and make it suitable for a very wide range of problems. The strength of the process lies in its ability to help the decision-maker identify and consider all pertinent factors and then to provide a range of models to evaluate the more complex stages of the process. The flexibility of this process was highlighted in the range of decisions evaluated in this thesis. For example, case study 1 was carried out at a very high, conceptual level. Case studies 2 and 3 involved very detailed reliability analysis, due to the severity of the risks involved. Finally, case study 4, involved very detailed stakeholder analysis, due to the significant stakeholder conflict.

Each of the first four case studies was supported to varying extents by a third party facilitator. This had a number of effects, which helped the decision-making to be more thorough, more rational and more unbiased. Firstly, the decision facilitator was able to view the whole decision problem independently. The decision facilitator also saw the problem as part of the bigger picture, without the prejudices and possible blinkered experiences of the decision-maker. This enabled increased creativity and lateral thinking in terms of identifying stakeholders, alternative solutions and risks. The decision facilitator's experience in the use of decision analysis methods also helped in applying the various models within the risk-based decision process and knowing when

different methods of analysis were more appropriate than others. It also ensured that the information available was used to the best advantage. The decision facilitator, through experience, showed confidence in the process and its application to the problem. The decision facilitator, through independent unbiased views, brought confidence in the fairness and rationality of the decision process to all stakeholders. This encouraged ownership and support for the decision and motivation for its implementation.

The risk-based decision process has been shown to provide support and guidance at every stage of decision-making for every type of decision considered here. The degree of benefit depends on the decision complexity, but the benefit is significant for all decisions considered as the process prompts consideration of issues and factors which may not otherwise be taken into account. Issues such as stakeholder influences, risks and multiple decision criteria that would often be pushed aside as irrelevant or difficult to handle can be incorporated into the decision process with clarity and fairness. The availability of an experienced and independent facilitator is of equal importance to ensure a rational and fair decision is made for all parties in decisions involving conflict.

12.9 Contributions to Risk-based Decision-making

The research presented in this thesis has made a significant contribution to the support of risk-based decision making for the management of structural assets in a number of areas. These are summarised schematically in Figure 43 and are discussed below.

12.9.1 Enhancement of the decision process

A number of shortcomings were identified in the decision processes described in the literature, for example, Keeney and Raiffa's decision process. These gaps included:

- Failure to identify and involve stakeholders in the decision;
- Not identifying and evaluating decision objectives and criteria;
- Not accounting for preferences between criteria and decision outcomes;
- Not evaluating the effect of important parameters on the final decision;
- Failure to monitor and control the implementation of the decision to ensure that objectives are met and risks are controlled.

A more comprehensive model was developed to address these issues. The additional steps are shown as shaded boxes in Figure 43. The enhanced model was used as the basis for applying the methods to real life decision problems.

12.9.2 Application of the decision process to real life decision problems

The enhanced decision process is based on a theoretical analysis of the generic decision making problem. The application of the process to a number of real life decision problems has demonstrated the usefulness of the model in practice. It has brought significant benefit and understanding in four very disparate case studies. Case study 5 has, in contrast, shown the weakness of decision making without the support of a rational systematic process. The successful application of the proposed enhanced

decision process to the solution of real life decision problems, in a way that fully accounts for all the important issues, is a significant contribution to this field.

12.9.3 Applicability of decision tools to real life case studies

Within each case study analysed, it was necessary to apply appropriate tools and techniques at each stage in the decision process. These tools and techniques had been identified by the literature review, however some had been found to be more useful than others for different types of decision problems. The experience from the case studies has allowed general guidelines to be developed to help decision-makers identify the levels and type of analysis most appropriate to different types of decision problems. The guidelines have been developed in the form of applicability matrices, as shown in Figures 34 to 39 and are summarised in Figure 43. The guidelines mean that the decision-makers can readily identify the resources appropriate to any particular decision problem without the need for detailed analysis.

12.9.4 Support of risk based decision making through facilitation

In each of the case studies, the potential benefits of third party facilitation have been assessed. This has been done in terms of the different roles that a facilitator might undertake. The roles considered here, of leader, liaison, disseminator, spokesman and disturbance handler, have all been found to be a significant part of decision facilitation and can often provide benefit if provided by an independent third party. The balance between these five roles within the decision process was also found to be important, as shown in Figure 43, to ensure the decision is not dominated by the facilitator.

12.10 Limitations of Research

This thesis has demonstrated the benefits that risk based decision methods can bring to the management of structural assets. It has not, however, exhaustively addressed every aspect of risk based decision making and is therefore subject to a number of limitations. These limitations are discussed below:

12.10.1 Limited use of decision tools

The literature review carried out at the start of this research identified a number of decision tools available to support every identified stage of the decision process. Only a fraction of these have been applied in the case studies as part of this research. The selection of appropriate tools was made for each case study based on the amount of information available, the timescale for the decision and the level of detail required. Some of these tools are well developed and provide a thorough understanding of the problem at that stage, such as tools for quantifying probability of failure. Other tools, for example, Saaty's analytic hierarchy process, were modified thoroughly as part of this research to make them more applicable to the problem. Because of the limited number of case studies, there was limited opportunity to use and evaluate some of the tools. Many of the tools not used within the case studies may themselves require similar modification to make them fully applicable.

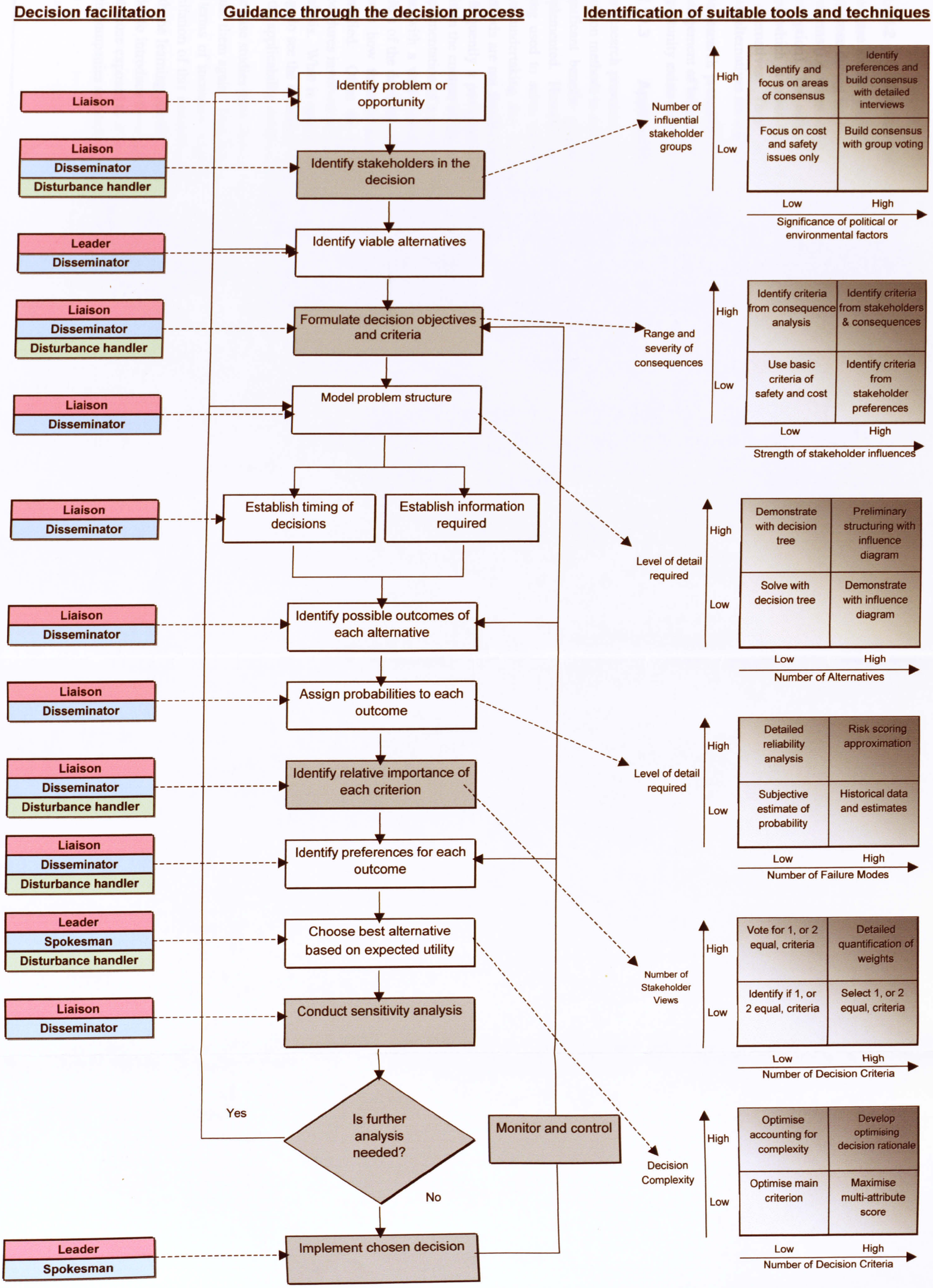


Figure 43: Schematic representation of the contribution of this research to risk based decision-making

12.10.2 Application to limited decision types

The case studies analysed in this research were limited by the decision opportunities that arose during the period of the research and only addressed evaluation type decision problems (i.e. where there is a finite set of possible alternatives from which to select the best option). The other type of decision problem, described in Chapter 2, is the design type, which involves the identification of an optimum solution based on an infinite set of alternatives. These decisions are less common in structural asset management as most alternatives are constrained into discrete values.

The research presented here has also only addressed two main application areas, the management of bridges and the management of subsea oil and gas pipelines. Significant opportunity exists to expand this research into new fields, as discussed below.

12.10.3 Applicability to real life decision problems

The research presented in this thesis has demonstrated the applicability of the proposed decision methods to real life decision problems. It has also demonstrated the potentially significant benefits associated with the way in which decisions are evaluated and implemented. However, this raises the question of why these methods are not already being used to solve engineering decision problems today. Based on my experience from undertaking this research, I would suggest firstly, that the majority of decision methods are not familiar to engineering decision makers. When they are known, there is frequently a perception that the methods are difficult and time consuming to apply. Within the context of the case studies, this has been proven to be wrong. The successful implementation of a poorly evaluated decision can take much longer than would be the case with a well-evaluated decision. Another barrier to using these methods is the failure of the decision-maker to recognise the availability of alternatives. Case study 5, shows how there is a danger of decisions evolving without ever being formally identified. Often the problem can be that the decision-makers are aware of the procedures involved in decision analysis, but these appear to them to significant detailed analysis. What is needed also, therefore, is an understanding of how to carry out each stage to see the efficiency with which the problem can be evaluated. This is the benefit of the applicability matrices developed in this thesis.

The case studies have shown that people exposed at first hand to these methods are keen to use them again. They have learnt the benefits brought to the decision making process in terms of increased confidence in the solution and consensus in its selection. A limitation of this research and an opportunity for further research, is the evaluation of both the learning process and the cultural change that an organisation has to undergo in order to introduce these methods as a standard tool in decision making. It is my belief that those exposed to these techniques in this research will be ambassadors for them in their companies and look for opportunities to use them again in the future.

12.11 Recommended Areas for Further Work

The limitations identified in this work above, provide a number of opportunities for further work to be carried out. These will be summarised here.

12.11.1 Recommended further development of tools

A number of the available tools lack efficiency, either in terms of ease of use or in terms of thoroughness. These are predominantly the identification tools. These tools are currently limited in effectiveness by the limited vision of the decision group as they all rely on brainstorming type methods. The success of these stages of the decision process relies entirely on the underlying knowledge of the decision group and its ability to conceptualise the problem and see what might happen. For example, tools for identifying viable alternatives are basically brainstorming based methods that rely on the creativity of the decision group and its capacity for lateral thinking. This makes it likely, especially in novel areas or with an uninspired decision group, that potentially good alternatives could be missed. The development of a knowledge based brainstorming tool could support the identification of experience, learning from experience and support the brainstorming of alternatives based on these. Such a tool could additionally use generic creativity and lateral thinking techniques. This could support the generation of a more thorough set of alternatives on more informed basis.

The other type of tools which would benefit from further development are risk identification tools. Current methods such as FMECAs (Failure Modes and Effects Criticality Analysis), HAZIDS (Hazard Identification Studies) and HAZOPS (Hazard and Operability Studies) are based on brainstorming techniques. The success in identifying all risks is dependent on the experience and expertise of the analysts involved. These tools would benefit from further development in order to introduce an element of knowledge and learning as well as creativity and lateral thinking.

The third area in which there is opportunity to develop further tools is in the identification of preferences for different outcomes. This very complex and time-consuming stage is frequently neglected as not being worth the required effort. The method of multi attribute utility theory proposed by Keeney and Raiffa [23] is the most widely known method but also the most time consuming and difficult to evaluate. The simplified version of this developed by Edwards [109] is more straightforward to apply but there is still a gap between the theories and the practicality of using them. Further work should therefore be carried out to make these methods even more straightforward to use, to require less demanding quantified comparisons and less time to evaluate. This could be used to determine when such evaluations would bring benefit to the decision-making process and when they would not.

Finally, at a slightly higher level, there is the potential for the whole risk-based decision process to be converted in to a computer-based diagnostic tool itself. This tool would not make the decisions on behalf of the decision maker. This was stated very early on in the thesis not to be the purpose of decision analysis. However, through a series of questions and check boxes, a diagnostic tool could guide the decision maker through the

risk-based decision process, to help identify the level of analysis required at each stage and select the most appropriate tools to support each stage. This is a step on from the idea of using the process as a checklist and incorporates the recommendations encompassed in the applicability matrices presented in the discussion. Such a computer-based diagnostic could help make the risk-based decision process more attractive and easier to use in a wider range of decision problems.

12.11.2 Recommended further application areas

As already stated, the research presented in this thesis has only addressed evaluation type decision problems. A further extension to the research would be to apply the methods to design type decisions. These decisions would not fit directly into the risk-based decision process presented here due to the iterative optimisation process usually adopted to solve these problems. The decision process would, however, serve as a valuable checklist to ensure all factors were accounted for, but might have to be modified further if it was to support these decisions at a more detailed level.

The research could also be expanded to address similar problems of high cost, high risk and high stakeholder values in many different application areas, which could also benefit from this work. For example, high value high profile construction projects such as the Millennium dome and the London Eye raise a large number of stakeholder issues, but also involve significant project and design risk. Applying these methods to these decisions would ensure all stakeholders and all risks were accounted for and provide an audit trail of the whole project to prove the rationality of the decisions. This is obviously of further benefit for projects that also have a high political profile.

Another high risk, high cost, high profile application area, although not involving risk of structural failure in the engineering sense, is the area of large IT projects. Again, these projects involve significant project and design risks and a large number of significant stakeholder issues, especially if these projects are for government departments or large utility providers.

There are many areas of potential application for these risk-based decision methods. In all areas of life and business difficult decisions impacting on varying groups of stakeholders have to be made under conditions of risk and uncertainty. Although the types of risks may vary together with the methods for quantifying them, the risk-based decision process presented here can provide support in order to ensure fairer, more rational and more auditable decisions.

13 REFERENCES

1 UKOOA. Industry issues: Piper Alpha. http://www.ukooa.co.uk/issues/PiperAlpha/v0000864.htm. (13th December 1999).

2 Shell Expro. Brent Spar homepage. http://www.shellexpro.brentspar.com/shell/brentspar/home.html. (13th December 1999).

3 BBC Education. Disaster: The Challenger shuttle. http://www.bbc.co.uk/education/archive/disaster/challeng.shtml. (13th December 1999).

4 Smith, N. J. (ed.) (1996). Engineering project management. Blackwell Science.

5 Edwards, C., Ward, J. and Bytheway, A. (1995). The essence of information systems. 2nd Edition. Prentice Hall, Hemel Hempstead.

6 The Royal Society (1992). Risk: analysis, perception and management. The Royal Society, London.

7 Belton, V. (1990). **Multiple criteria decision analysis - practically the only way to choose.** In: Hendry, L. C. and Eglese, R. W. (eds), Operational research tutorial papers. Operational Research Society.

8 Goodwin, P. and Wright, G. (1991). Decision analysis for managerial judgement. John Wiley and Sons, Chichester.

9 Simon, H. (1957). Administrative Behaviour. Macmillan.

10 Dearborn, D. C. and Simon, H. A. (1958). **Selective perception: The identifications of executives.** Sociometry, vol. 21, 140-144.

11 Maslow, A. H. (1970). **A Theory of human motivation.** In: Vroom, V. H. and Deci, E. I. (eds.), Management and motivation, Penguin.

12 Bem, D. J. (1970). Beliefs, attitudes and human affairs. Brooks-Cole.

13 England, G. W. (1967). **Personal value systems of American managers.** Academy of management journal. March 1967, p54.

14 Lindsay, P. H. and Norman, D. A. (1972). Human information processing. Academic press.

15 Lee, W. (1971). Decision theory and human behaviour. John Wiley & Sons, New York.

16 Marshall, A. (1920). The principles of economics: An introductory volume, 8th Edition. Macmillan, London.

17 Ramsey, F. P. (1931). The foundations of mathematics. Harcourt Brace, New York.

18 Von Neumann, J. and Morgenstern, O. (1947). Theory of games and economic behaviour. Princeton University.

19 Mosteller, F. and Nogee, P. (1951). **An experimental measurement of utility.** Journal of political economy, vol. 51, 371-404.

20 Davidson, D., Suppes, P. and Siegel, S. (1957). Decision-making: An experimental approach. Stanford University, California.

21 Friedman, M. and Savage, L. J. (1948). **The utility analysis of choices involving risk.** Journal of political economy, 279-304.

22 Raiffa, H. (1968). Decision analysis: Introductory lectures on choices under uncertainty. Addison Wesley.

23 Keeney, R. L. and Raiffa, H. (1976). Decisions with multiple objectives: preferences and value trade-offs. John Wiley and Sons.

24 Clemen, R. T. (1991). Making hard decisions. PWS-Kent Publishing Company.

25 Brams, S. J. and Kilgour, D. M. (1988). Game theory and national security. Blackwell.

26 Haywood, O. G., Jr. (1954). **Military decision and game theory.** Operations research, no. 2, 365-385.

27 Ravid, I. (1990). **Military decision, game theory and intelligence: An anecdote.** Operations research, vol. 38, no. 2, 260-264.

28 Royal Military College of Science (1997). **A military appreciation.** In: Decision analysis course notes, Department of Applied Mathematics and Operational Research, School of Defence Management, RMCS.

29 Coyle, R. G. (1989). **A mission orientated approach to defence planning.** Defense analysis, vol. 5, no. 4, 353-367.

30 Krishnakumar, K. (1992). **Genetic algorithms: An introduction and an overview of their capabilities.** AIAA guidance, navigation and control conference, Report no. AIAA-92-4462-CP, 728-738.

31 Goldberg, D. E. (1989). Genetic algorithms in search, optimisation and machine learning. Addison Wesley Publishing Co.

32 Callahan, K. J. and Weeks, G. E. (1992). **Optimum design of composite laminates using genetic algorithms.** Composite engineering, vol. 2, no. 3, 149-160.

33 Frank, M. V. (1990). **Deciding among risk reduction measures in the face of uncertainty.** AIAA space programs and technologies conference, AIAA 90-3878, American Institute of Aeronautics and Astronautics.

34 Bath, U. et. al. (1995). **Pilot methods, integration of methods of task 3.1 with tasks 3.2 and 3.3.** BRITE-BE 5935, Report TEC-T3_4_01.

35 Holst, O., Sorensen, B. (1984). **Combined scheduling and maintenance planning for an aircraft fleet.** Operational research '84, 474-486, Elsevier Science.

36 Lee, K. R. and Reno, R. W. (1978). **Aircraft maintenance scheduling.** AGIFORS symposium proceedings, vol. 18, 235-256.

37 Konig, P. (1976). **Short-term aircraft assignment.** AGIFORS symposium, vol. 16, 165-193.

38 Dekker, R. (1996). **Applications of maintenance optimisation: A review and analysis,** Reliability engineering and systems safety, no. 51, 229-240.

39 Barlow, R. E. and Proschan, F. (1965). Mathematical theory of reliability. John Wiley, New York.

40 McCall, J. J. (1965). **Maintenance policy for stochastically failing equipment: A survey.** Management science, no. 11, 493-524.

41 Mayer, R. R. (1960). **Problems in the application of replacement theory.** Management science, no. 6, 303-310.

42 Turban, E. (1967). **The use of mathematical models in plant maintenance decision-making.** Management science, no. 13, 342-358.

43 Davidson, D. (1970). **An overhaul policy for deteriorating equipment.** In: Jardine, A. (ed), Operational research in maintenance. Manchester University Press.

44 Mahon, B. H. and Bailey, R. J. M. (1975). **A proposed improved replacement policy for army vehicles.** Operations research quarterly, no. 26, 477-494.

45 Pierskalla, W. P. and Voelker, J. A. (1979). **A survey of maintenance models: The control and surveillance of deteriorating systems.** Naval research logistics quarterly, no. 23, 353-388.

46 Anderson, R. T. and Neri, L. (1990). Reliability centred maintenance, management and engineering methods. Elsevier Science, London.

47 Vatn, J., Hokstad, P. and Bodsberg, L. (1996). **An overall model for maintenance optimisation.** Reliability engineering and system safety, no. 51, 241-257. Elsevier Science.

48 Vesely, W. E., Belhadj, M. and Rezos, J. T. (1994). **PRA importance measures for maintenance prioritisation applications.** Reliability engineering and system safety, no. 43, 307-318. Elsevier Science.

49 Gore, B. F., Vo, T. V. and Simonen, F. A. (1989). **Development of risk-based inspection guidance.** 1989 winter annual meeting of the american society of mechanical engineers, 115-120. ASME.

50 Hontelez, J. A. M., Burger, H. H. and Wijnmalen, D. J. D. (1996). **Optimum condition-based maintenance policies for deteriorating systems with partial information.** Reliability engineering and system safety, no. 51, 267-274. Elsevier Science.

51 Legat, V., Zaludova, H., Cervenka, V. and Jurca, V. (1996). **Contribution to optimisation of preventive replacement.** Reliability engineering and system safety, no. 51, 259-266. Elsevier Science.

52 Aven, T. (1996). **Condition based replacement policies – A counting process approach.** Reliability engineering and system safety, no.51, 275-281. Elsevier Science.

53 Dekker, R., Smit, A. and van Rijn, C. (1994). **Mathematical models for the optimisation of maintenance and their application in practice.** Maintenance, no. 9, 22-26.

54 Farid, F., Johnston, D. W., Rihani, B. S. and Chen, C. J. (1994a). **Feasibility of incremental benefit-cost analysis for optimal budget allocation in bridge management systems.** Transportation research record no. 1442: Maintenance of highway infrastructure, 77-87. National Academy Press, USA.

55 Farid, F., Johnston, D. W., Laverde, M. A. and Chen, C. J. (1994). **Application of incremental benefit-cost analysis for optimal budget allocation to maintenance, rehabilitation and replacement of bridges.** Transportation research record no. 1442: Maintenance of highway infrastructure, 88-100, National Academy Press, USA.

56 Augusti, G., Borri, A. and Ciampoli, M. (1992). **Optimal allocation of resources in repair and maintenance of bridge structures.** Proceedings of the 6th ASCE speciality conference on probabilistic mechanics, and structural and geotechnical reliability.

57 Weissmann, J., Harrison, R., Burns, N. H. and Hudson, W. R. (1990). **Selecting rehabilitation and replacement bridge projects.** In: Maupin Jr., G., Brown, B. and Lichtenstein, A. (eds), Extending the life of bridges, ASTM STP 1100, 3-17, ASTM, USA.

58 Thoft-Christensen, P. (1993). **Reliability-based expert systems for optimal maintenance of concrete bridges.** Proceedings of the symposium on structural engineering in natural hazards mitigation. 1053-1058, ASCE, USA.

59 Lindley, D. V. (1976). Introduction to probability and statistics from a Bayesian viewpoint, vol. 1 and 2, Cambridge University Press.

60 Sommer, A. M., Nowak, A. S. and Thoft-Christensen, P. (1993). **Probability based bridge inspection strategy.** Journal of structural engineering, vol. 119, no. 12, 3520-3535, ASCE, USA.

61 Cesare, M.; Santamarina, J. C.; Turkstra, C. J.; Vanmarcke, E.; (1992). **Modelling bridge deterioration with Markov chains.** ASCE journal of transportation engineering, vol. 118, no. 6, 820-833, ASCE.

62 Cesare, M.; Santamarina, J. C.; Turkstra, C. J.; Vanmarcke, E., (1993). **Risk-based bridge management.** Journal of transportation engineering, vol. 119, no. 5, ASCE.

63 Cesare, M.; Santamarina, J. C.; Turkstra, C. J.; Vanmarcke, E., (1994). **Risk-based bridge management: Optimisation and inspection scheduling.** Canadian journal of civil engineering, vol. 21, no. 6, 897-902.

64 Frangopol, D. M. and Estes, A. C. (1997). **Lifetime bridge maintenance strategies based on system reliability.** Structural engineering international, no. 3, 193-198.

65 American Petroleum Institute (1993). Recommended practice for planning, designing and constructing fixed offshore platforms. API RP2A, 20th ed., API.

66 Banon, H. (1994). **Assessing fitness for purpose of offshore platforms. II: Risk management, maintenance and repair.** Journal of structural engineering, vol. 120, no. 12, 3613-3633. ASCE, USA.

67 Wirsching, P. H. and Torng, Y. (1989). **Optimal strategies for design, inspection and repair of fatigue sensitive structural systems using risk-based economics.** Proceedings of the 5th international conference on structural safety and reliability, ICOSSAR '89, 2107-2114.

68 Harris, D. O. (1992). **Probabilistic fracture mechanics with application to inspection planning and design,** Reliability Technology, AD vol. 28, 57-76, ASME, USA.

69 Jiao, G. (1992). **Reliability analysis of crack growth with inspection planning.** Proceedings of the symposium on offshore mechanics and arctic engineering, OMAE '92, vol. II, 227-235, ASME, USA.

70 Tanaka, H. and Toyoda-Makino, M. (1998). **Cost-based optimal relation between inspection time and assessment time for random fatigue crack growth.** Probabilistic engineering mechanics, vol. 13, no. 2, 69-76. Elsevier Science.

71 Platform Reliability Inspection Scheduling & Maintenance Ltd. (1994). **RISC – reliability based inspection scheduling for fixed offshore platforms: A knowledge based system incorporating reliability based inspection planning methods,** Promotion of energy technologies for europe, no. 187, CEC, Brussels.

72 Dharmavasan, S., Peers, S. M. C., Faber, M. H., Dijkstra, O. D., Cervetto, D. and Manfredi, E. (1994). **Reliability based inspection scheduling for fixed offshore structures.** Proceedings of the symposium on offshore mechanics and arctic engineering, OMAE '94, vol. II, 227-235, ASME, USA.

73 Faber, M. H., Dharmavasan, S. and Dijkstra, O. D. (1994). **Integrated analysis methodology for reassessment and maintenance of offshore structures.**

Proceedings of the symposium on offshore mechanics and arctic engineering, OMAE '94, vol. II, 237-244, ASME, USA.

74 Dijkstra, O. D., van Foeken, R. J. and Dharmavasan, S. (1994). **Fracture mechanics limit states for assessment and maintenance planning of offshore structures.** Proceedings of the symposium on offshore mechanics and arctic engineering, OMAE '94, vol. II, 245-252, ASME, USA.

75 Goyet, J., Faber, M. H., Paygnard, J.-C. and Maroini, A. (1994). **Optimal inspection and repair planning: case studies using IMREL software.** Proceedings of the symposium on offshore mechanics and arctic engineering, OMAE '94, vol. II, 325-333, ASME, USA.

76 Enevoldsen, I. and Sorensen, J. D. (1994). **Reliability-based optimisation in structural engineering,** Structural Safety, no. 15, 169-196. Elsevier Science.

77 Faber, M. H., Kroon, I. B. and Sorensen, J. D. (1996). **Sensitivities in structural maintenance planning,** Reliability engineering and system safety, no. 51, 317-329. Elsevier Science.

78 Kiefner, J. F., Vieth, P. H., Orban, J. E. and Feder, P. I. (1990). Methods for prioritising pipeline maintenance and rehabilitation. American Gas Association.

79 Muhlbauer, W. K. (1992). Pipeline risk management manual. Gulf Publishing Company, Texas.

80 Concord Environmental Corporation (1993). Risk assessment techniques for pipeline systems, prepared for the Pipeline Environmental Committee of the Canadian Association of Pipeline Producers, Calgary, Canada.

81 Hill, R. T. (1992). **Pipeline risk analysis.** Institute of chemical engineers symposium series, no. 130, 637-670.

82 Urednicek, M., Coote, R. I. and Coutts, R. (1992). **Optimising rehabilitation process with risk assessment and inspection.** Proceedings of the international conference on pipeline reliability, Calgary, II-12-1 to II-12-14.

83 Kirkwood, M. G. and Karam, M. (1995). **Priority rating scheme guides maintenance, rehab decisions.** Pipeline and gas industry, July 1995, 21-28.

84 Nessim, M. A. and Stephens, M. J (1995). **Risk-based optimisation of pipeline integrity maintenance.** Proceedings of the symposium on offshore mechanics and arctic engineering, OMAE '95, vol. V, 303-314, ASME, USA.

85 Cooke, S. and Slack, N. (1984). Making management decisions. Prentice Hall.

86 Von Winterfeldt, D. and Edwards, W. (1986). Decision analysis and behavioural research. Cambridge University Press.

87 Belton, V. and Pictet, J. (1996). A framework for group decision using a MCDA model: Sharing, aggregating or comparing individual information. University of

Strathclyde, Glasgow, Management Science, Theory, Method and Practice Working paper 96/16.

88 De Bono, E. (1982). De Bono's thinking course. Pitman Press.

89 Gardiner, P. C. (1977). **Decision spaces.** IEEE transactions on systems, man and cybernetics, vol. SMC-7, no. 5, May 1977.

90 Walker, W. (1988). **Generating and screening alternatives.** In: Miser, H. and Quade, E. (eds), Handbook of systems analysis: Craft issues and procedural choices. Wiley.

91 Gescha, H., Schaude, G. R. and Schicksupp, H. (1973). **Modern techniques for solving problems.** Journal of Chemical Engineering, August 1973.

92 Pearl, J. (1977). **A framework for processing value judgements.** IEEE transactions on systems, man and cybernetics, vol. 7, 349-354.

93 Friend, J. and Hickling, A. (1987). Planning under pressure. Pergammon Press.

94 Howard, N. (1971). Paradoxes of rationality: Theory of metagames. MIT Press, London.

95 Bennett, P. G. and Huxham, C. S. (1982). **Hypergames and what they do: A soft 'OR Approach'.** Journal of the operational research society, 33, 41-50.

96 Rosenhead, J. (ed) (1989). Rational analysis for a problematic world. Wiley.

97 Howard, R. A. (1988). **Decision analysis: Practice and promise.** Management science, 34, 679-695.

98 Waters, C. D. J. (1989). A practical introduction to management science. Addison Wesley Publishing.

99 Hauge, I. H. and Wright, J. F (1995). **A multi-criteria risk management model.** 46th international astronautical congress, 2-6 October 1995, Oslo Norway. International astronautical federation report IAF-95-IAA.6.2.06.

100 Saaty, T. L. (1990). **How to make a decision: The analytic hierarchy process.** European journal of operational research, vol. 48, 9-26.

101 Luce, R. D. and Raiffa, H. (1957). Games and decisions. Wiley, New York.

102 Hertz, D. B. (1964). **Risk analysis in capital investment.** Harvard business review, Jan/Feb 1964, 95-106.

103 Melchers, R. E. (1987). Structural reliability analysis and prediction. John Wiley and Sons.

104 Thoft-Christensen, P. and Baker, M. J. (1982). Structural reliability theory and its applications. Springer Verlag, Germany.

105 Ditlevsen, O. and Madsen, H. O. (1996). Structural reliability methods. John Wiley and Sons.

106 RCP GmbH (1997). SYSREL - Structural systems reliability analysis software.

107 Benjamin, J. R. and Cornell, C. A. (1970). Probability, statistics and decision for civil engineers. McGraw-Hill.

108 Shetty, N. K., Chubb, M. S. and Halden, D. (1996). **An overall risk-based assessment procedure for substandard bridges.** In: International symposium on safety of bridges, Institution of Civil Engineers, London.

109 Edwards, W. (1977). **How to use multi-attribute utility measurement for social decision-making.** IEEE transactions on systems, man and cybernetics, vol. SMC-7, no. 5, May 1977.

110 Lagreze, E. J. and Shakun, M. F. (1984). **Decision support systems for semi-structured buying decisions.** European journal of operational research, no. 16, 48-58.

111 Rohrbaugh, J. and Wehr, P. (1978). **Judgement analysis in policy formulation: A new method for improving public participation.** Public Opinion Quarterly, no 43, 521-532.

112 Roy, B. (1973). **How outranking helps multiple criteria decision-making.** In: Cochrane, J. L. and Zeleny, M. (eds), Multiple criteria decision-making, University of South Carolina Press.

113 Roy, B. and Hugonnard, J. C. (1982). **Ranking of suburban line extension projects on the Paris metro by a multi-criteria method.** Transportation research, no. 16A, 301-312.

114 Brans, J. P., Mareschal, B. and Vincke, P. H. (1986). **How to select and how to rank projects: The PROMETHEE method.** European journal of operational research, no. 24, 228-238.

115 Bayes, T. (1763). **An essay towards solving a problem in the doctrine of chances.** Philosophical transactions of the Royal Society, vol. 53, 370-418.

116 Howard, R. A. (1970). **Risk preference.** In: Howard, R. A. and Matheson, J. E. (eds), Readings on the principles and applications of decision analysis, Vol. 2: Professional Collection. Strategic Decisions Group 1984, USA.

117 Adams, E. W. (1960). **Survey of Bernoullian utility theory.** In Solomon, H. (ed), Mathematical thinking in the measurement of behaviour. The Free Press.

118 Wald, A. (1950). Statistical decision functions. Wiley, New York.

119 Savage, L. J. (1954). The foundations of statistics. Wiley, New York.

120 Laplace, P. S. (1951). A philosophical essay on probabilities. Dover, New York.

121 Hausner, M. (1954). **Multidimensional utilities.** In: Thrall, R. N., Coombs, C. H. and Davis, R. L. (eds), Decision processes, 167-180, Wiley, New York.

122 Ingersoll, J. E. (1987). Theory of financial decision-making. Rowman and Littlefield Publishers.

123 UKOOA, (1998). **A framework for risk related decision support.** A draft report by the united kingdom offshore operators association, August, 1998.

124 Highways Agency, (1995). **BD44/95, The assessment of concrete highways bridges and structures.** Design manual for roads and bridges. Vol 3b: Highways structures inspection and maintenance, section 4: Assessment, Part 14. HMSO.

125 Kennedy-Reid, I. L. (1996). Motorway viaducts - risk-based strategy: Discussion document on bond. WSA ref.: AU2225/15/064/2/D1.

126 Martin, H., Rausen, A., Schiessl, P. (1975). **Carbonation of concrete made with different types of cement.** Colloquium on the behaviour in service of concrete structures, Liege.

127 Klopfer, H. (1981). **The carbonation of external concrete and how to combat it.** One day conference on the repair of concrete structures, Imperial College, London.

128 Parrott, L. J. (1987). **A review of carbonation in reinforced concrete.** Cement and concrete association & building research station, UK.

129 Mallett, G. P. (1994). Repair of concrete bridges: A state-of-the-art review. Thomas Telford, UK

130 Wood, J. G. M. (1990). **Predicting future decay in concrete structures.** In: Somerville, G. (ed.), Colloquium on the design life of structures, Blackie, Glasgow, UK.

131 Cady, P. D., Weyers, R., E. (1992). **Predicting service life of concrete bridge decks subject to reinforcement corrosion.** In: Chaker, V. (ed.), ASTM STP 1137: Corrosion forms and control for infrastructure. p328-338, ASTM, Philadelphia, USA.

132 Somerville, G. (1986). **The design life of concrete structures.** The structural engineer, Vol. 64A, No. 2, Feb 1986, p 60-71, Institution of Structural Engineers.

133 Rostam, S., Geiker, M. (1993). Prediction of residual service life: conversion from theory to practical engineering. COWIconsult, Denmark.

134 Skaarup, J., de Fontenay, C. (1987). **The influence of exposure conditions on the rate of carbonation of different concretes in Bahrain.** 2nd international conference on deterioration and repair of reinforced concrete in the Arabian Gulf, October, 1987.

135 Pocock, D. C., Gibbs, B. (1986). **Diagnosis, prevention and repair of deterioration in concrete bridges - an overview.** Sino-British highways and urban traffic conference, Beijing, Institution of Highways and Transportation.

136 Thoft-Christensen, P., Jensen, F. M., Middleton, C. R., Blackmore, A. (1996). **Revised rules for concrete bridges.** International symposium on the safety of

bridges: flexibility, risks and options in design, assessment & management, 4-5 July, 1996, Thomas Telford, London.

137 Miyagawa, T. (1991). **Durability design and repair of concrete structures: chloride corrosion of reinforcing steel and alkali-aggregate reaction.** Magazine of concrete research, Vol. 43, No. 156, Sept 1991, p 155-170.

138 Rodriguez, J., Ortega, L. M., Casal, J., Diez, J. M. (1996). **Assessing structural conditions of concrete structures with corroded reinforcement.** In: Dhir, R. K., Jones, M. R. (eds.) Concrete repair, rehabilitation and protection, E & FN Spon, London.

139 Wood, J. G. M. (1996). **Durability design: Applying data from materials research and deteriorated structures.** In: Harding, J. E., Parke, G. A. R., Ryall, M. J. (eds.) Proceedings of the 3rd international conferefence on bridge management. p 723-731, E and FN Spon, London, UK.

140 Wood, J. G. M., Wilson, J. R., Leek, D. S. (1989). **Improved testing for chloride ingress resistance of concretes and relation of results to calculated behaviour.** 3rd international conference on deterioration and repair of reinforced concrete in the Arabian Gulf, October, 1989.

141 Chatterji, S. (1995). **On the applicability of Fick's second law to chloride ion migration through portland cement concrete.** Cement and concrete research, Vol. 25, No. 2, p 299-303, Elsevier Science Ltd.

142 Gonzalez, J. A., Andrade, C., Alonso, C., Feliu, S. (1995). **Comparison of rates of general corrosion and maximum pitting penetration on concrete embedded steel reinforcement.** Cement and concrete research, Vol. 25, No. 2, p 257-264, Elsevier Science Ltd.

143 G. Maunsell and Partners (1996). Motorway viaducts - reliability-based repair strategy: deterioration modelling framework document.

144 Cooper, D. I. (1996). **Interim short span bridge assessment loading: Appendix 1: Amendments to BD 21/93: Preliminary draft proposals.** In: International symposium on safety of bridges, Institution of Civil Engineers, London.

145 Kennedy, D. J. L. et al (1992). **Canadian highway bridge evaluation: load and resistance factors.** Canadian journal of civil engineering, Vol. 19.

146 Joint Committee on Structural Safety (1996). **Eurocode random variables project.** JCSS Working Document, Confidential.

147 Madsen, H. O., Krenk, S. and Lind, N. C. (1986). Methods of structural safety. Prentice-Hall Inc., Englewood Cliffs, N.J.

148 RCP GmbH (1994). STRUREL: A structural reliability analysis program. Version 4.2, Copyright RCP GmbH, Germany.

149 Menzies, J. B. (1997). **Bridge failures, hazards and societal risk.** In: Das, P. (ed.), Safety of Bridges, Thomas Telford, London.

150 Shetty, N. K. (1997). Motorway viaducts - risk-based repair strategy: Methodology for level 5 assessment. WS Atkins AST/AU2766/Level 5, Confidential.

151 Chryssanthopoulos, M. K., Micic, T. V. And Manzocchi, G. M. (1997). **Reliability evaluation of short span bridges.** Das, P. (ed.), Safety of bridges, Thomas Telford, London.

152 Department of Transport (1984). **The assessment of highway bridges and structures.** Departmental standard BD21/84, HMSO London.

153 Nordic Committee on Building Regulations (1978). **Recommendations for loading and safety regulations for structural design.** NKB report no. 36.

154 Allen, D. E. (1992). **Canadian highway bridge evaluation index.** Canadian journal of civil engineering, Vol. 19.

155 de Waard, C., Lotz, U. and Dugstad, A. (1995). **Influence of liquid flow velocity on CO_2 corrosion: a semi-empirical model.** NACE Corrosion 95, Paper no. 128.

156 de Waard, C. and Lotz, U. (1993). **Prediction of CO_2 corrosion of carbon steel.** NACE Corrosion 93, Paper No. 69.

157 NORSOK (1998). NORSOK M-506, CO_2 corrosion rate model, Version 2.1, May 1998.

158 Rosenfeld, M. J., Kiefner, J. F. (1995). Proposed fitness-for-purpose appendix to the ASME B31.8 code for pressure piping - Section B31.8: Gas transmission and distribution systems, Kiefner and Associates, Worthington, Ohio, Jan. 1995.

159 Royal Military College of Science (1997). **Formalising subjective judgements.** In: Decision analysis course notes. Note 285. Department of Applied Mathematics and Operational Research, School of Defence Management.

160 Health and Safety Executive (1993). Quantified risk assessment: Its input to decision-making, HMSO, London.

161 Handy, C. B. (1985). Understanding organisations, 3rd Edition, Penguin Business.

162 Mintzberg, H. (1973). The nature of managerial work. Harper and Row.

APPENDICES

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APPENDIX 1 REVIEW OF DESIGN TYPE DECISION MAKING

A1.1 Introduction

Design type decision problems are concerned with identifying 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.

A1.2 Identify viable alternatives

In design type decision problems, even if the alternatives are not immediately obvious when the decision is defined, it is still straightforward to identify all possible alternatives, simply due to the way the mathematical programming solves the problem.

A1.3 Formulate decision objectives and criteria

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

A1.4 Utility/Value Analysis

Design type decision problems differ from evaluation type problems in that the alternatives are not defined explicitly, but implicitly by constraints. Most methods used to solve these problems involve mathematical programming. Multiple objective programming and Goal programming are the most widely used approaches. Objective functions are defined according to the objectives and preferences of the decision maker, for example to minimise cost, maximise capacity, etc. These objective functions are then optimised according to the constraints. If required, penalty functions can be defined instead of constraints, where alternatives can only exceed certain criteria values at a cost.

A1.5 Selection of "best" alternative

Objective functions created within design type decision problems are usually solved with calculus-based methods to find local extrema in the non-linear equations resulting from setting the objective function gradient to zero. However, this approach is not entirely robust as the optima sought are the best in the current point's neighbourhood. If the search starts in the wrong place, it could miss the main peak and converge on a lower peak. The search can be randomly restarted to improve the solution however this is still unreliable.

Enumerative search methods consider individual objective function values at each point. This is a very simple method unlikely to miss an optima, however, it is very inefficient.

A third and very popular method is random search, yet these are hardly more efficient than enumerative methods, if the final result requires a reasonable level of confidence. A more successful type of random choice is the use of genetic algorithms [1, 2]. These

are search algorithms based on natural selection mechanics 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 the fittest parts of the old set and adding occasionally a new part. They efficiently exploit historical information to speculate on new search points with expected improved performance.

Interactive methods have also been developed to take the decision maker "on a tour" of non dominated alternatives. At each stage, the decision maker identifies preferences until the most preferred alternative is identified.

APPENDIX 2 DETAILED DECISION TREES USED FOR EVALUATING CASE STUDY 1

Page

1. Evaluation of production risers option 1 (too large and cumbersome to be included)
2. Evaluation of production risers option 2 A5
3. Evaluation of gas lift risers option 1 A6
4. Evaluation of gas lift risers option 2 A8
5. Evaluation of dynamic umbilicals option 1 A9
6. Evaluation of dynamic umbilicals option 2 A11
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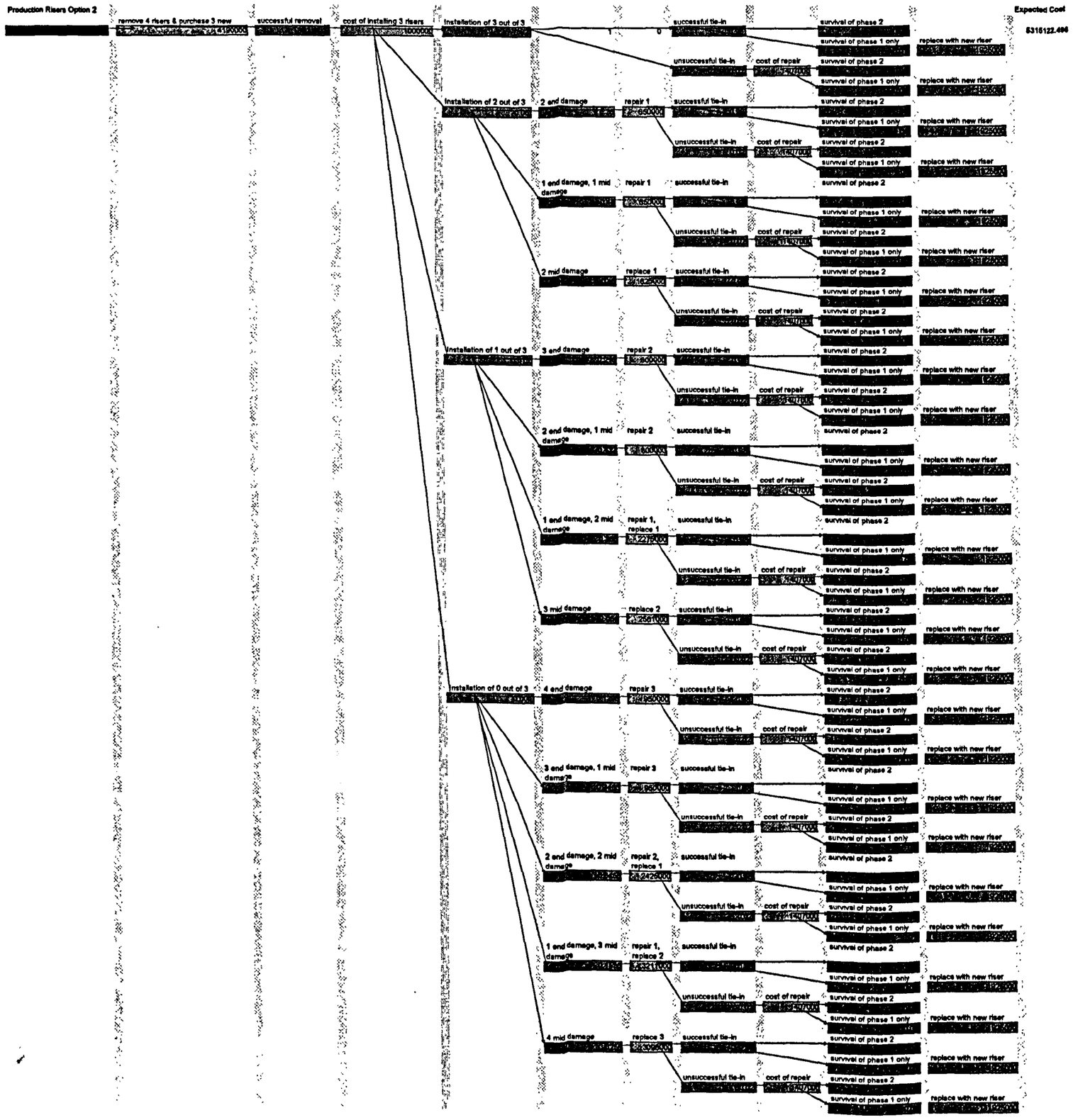
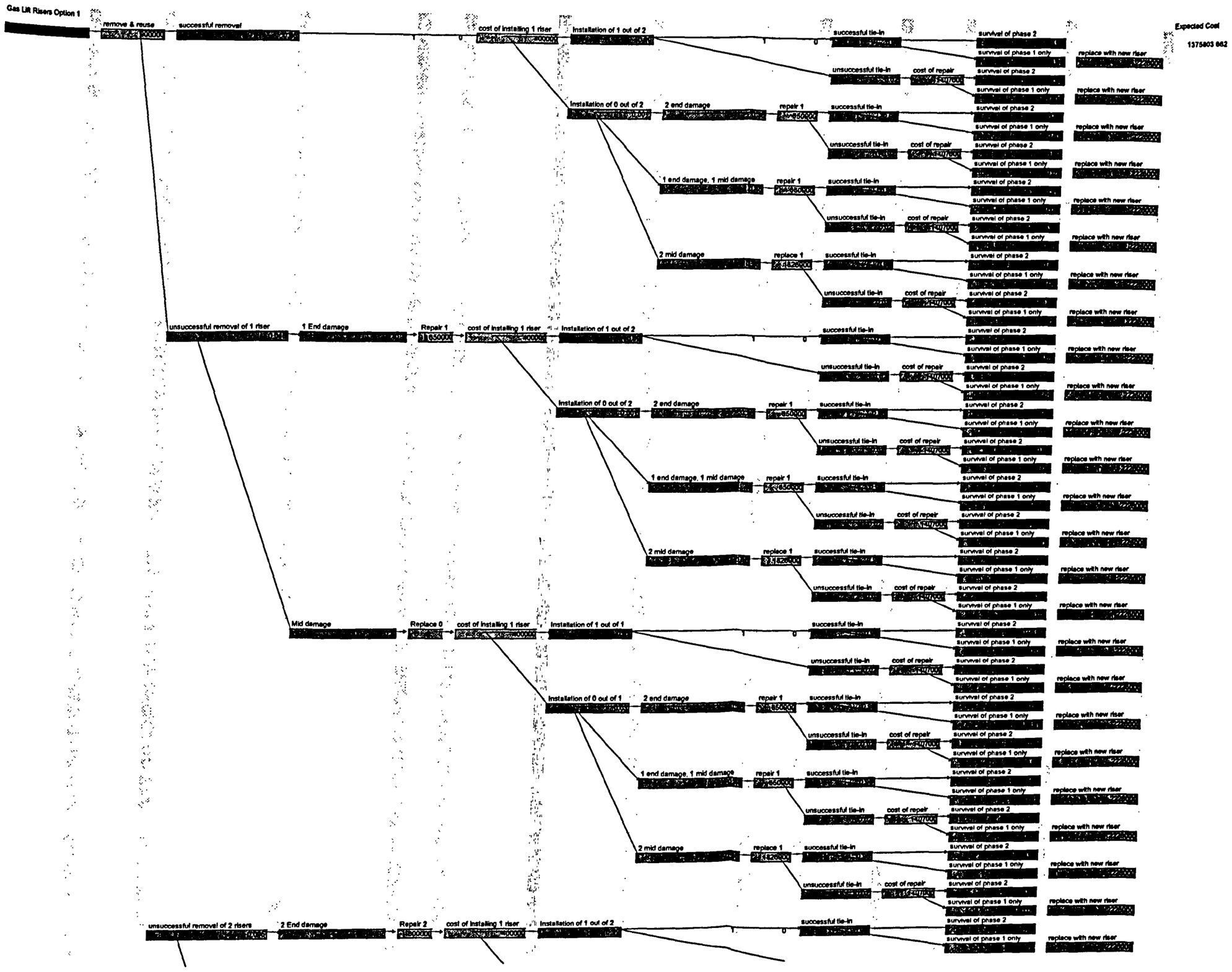
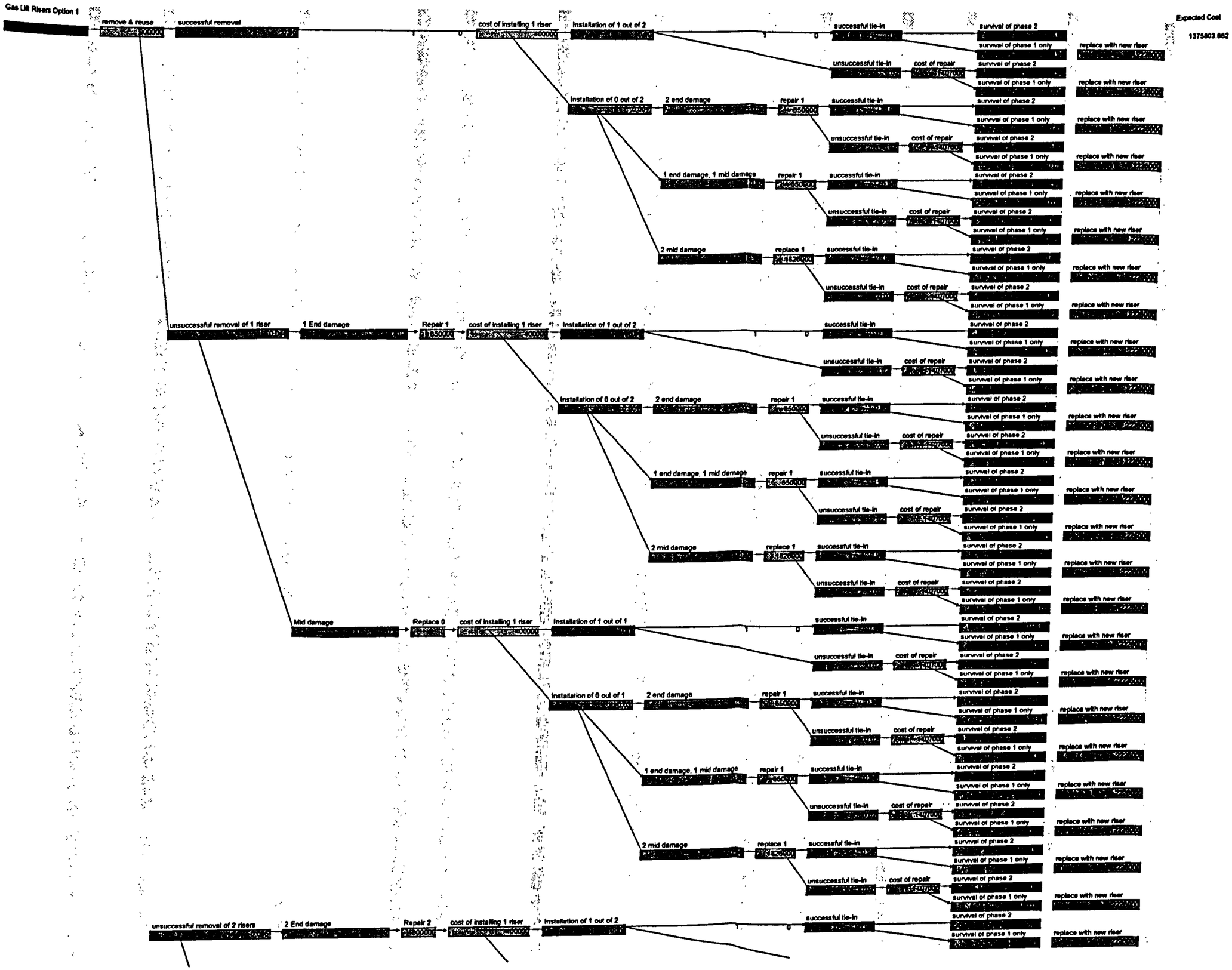
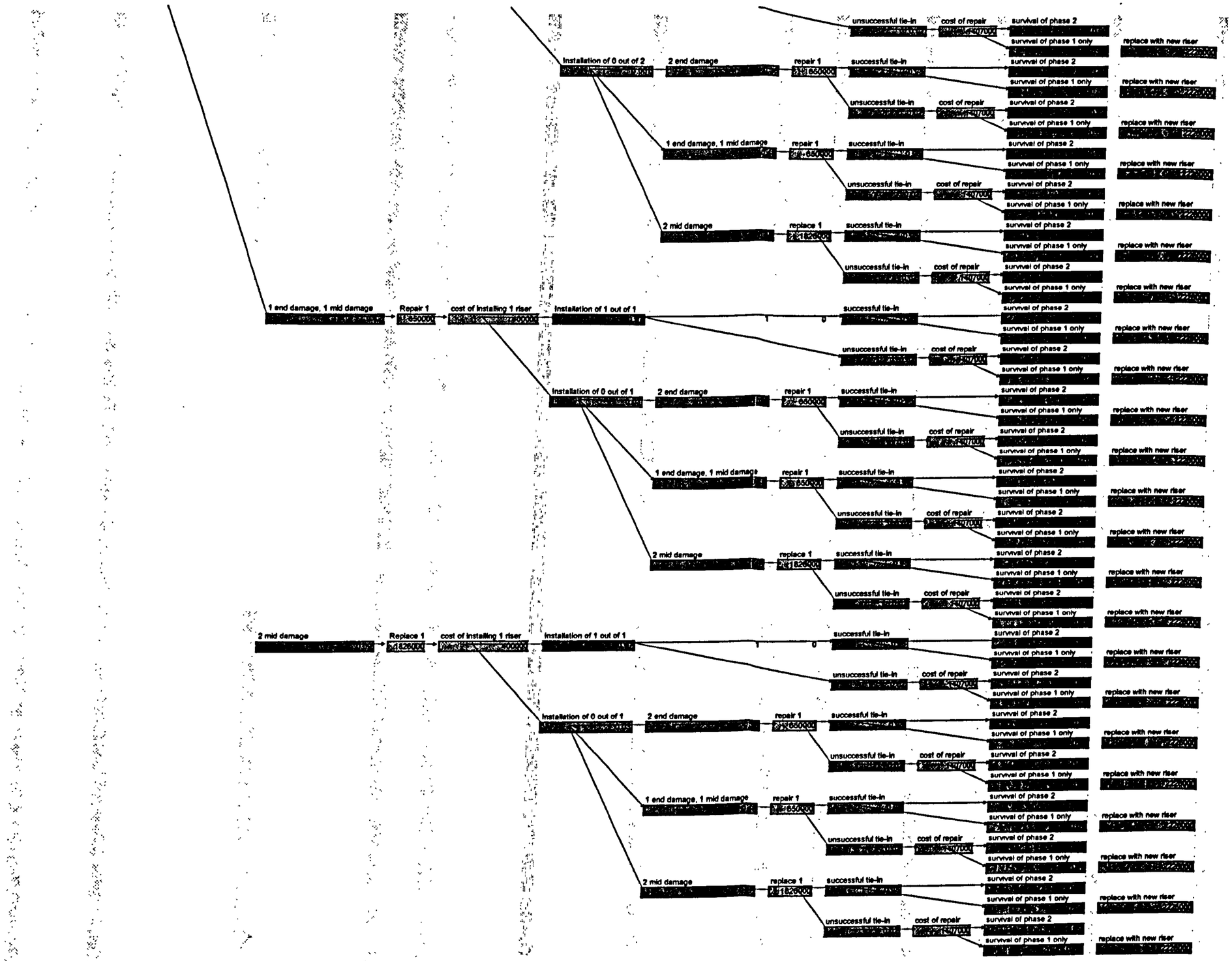
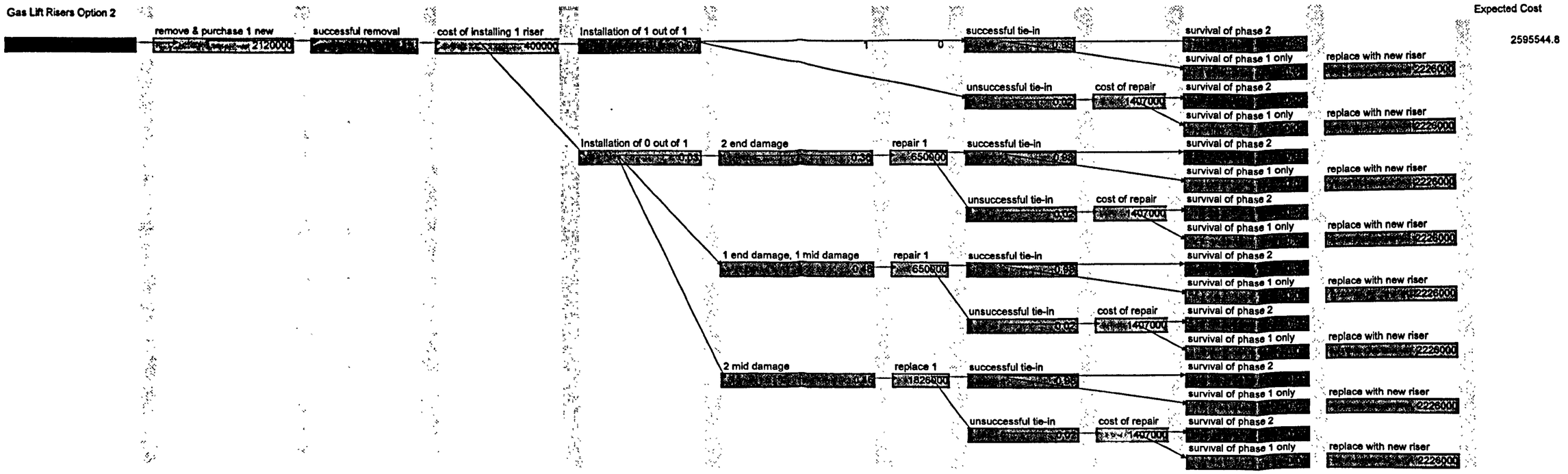
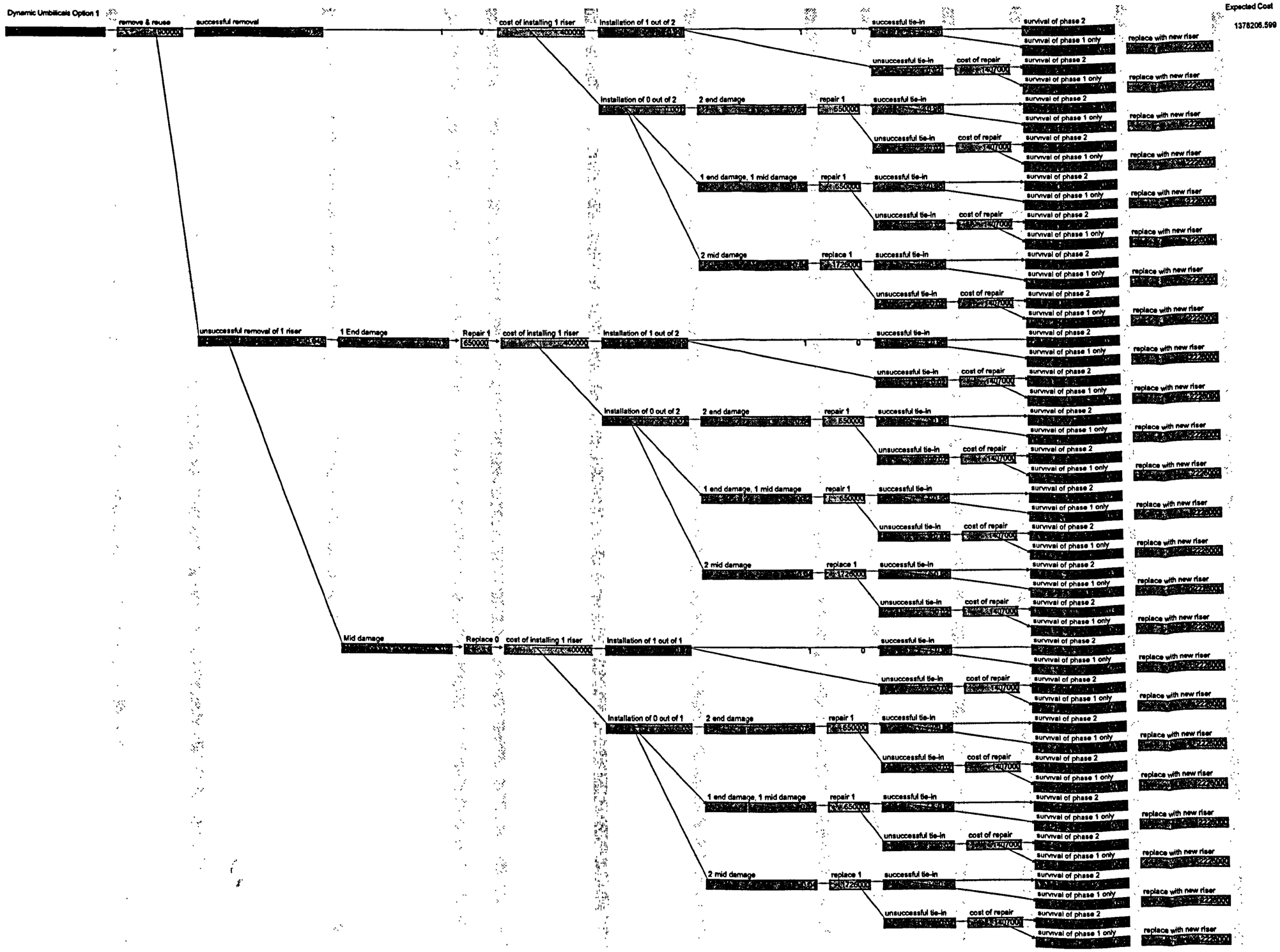

Production Risers Option 2
remove 4 risers & purchase 3 new
successful removal
cost of installing 3 risers
Installation of 3 out of 3
Installation of 2 out of 3
Installation of 1 out of 3
Installation of 0 out of 3
1
0
2 end damage
repair 1
1 end damage, 1 mid damage
2 mid damage
replace 1
3 end damage
repair 2
2 end damage, 1 mid damage
1 end damage, 2 mid damage
repair 1, replace 1
3 mid damage
replace 2
4 end damage
repair 3
3 end damage, 1 mid damage
2 end damage, 2 mid damage
repair 2, replace 1
1 end damage, 3 mid damage
repair 1, replace 2
4 mid damage
replace 3
successful tie-in
unsuccessful tie-in
cost of repair
survival of phase 2
survival of phase 1 only
replace with new riser
Expected Cost
5315122.496

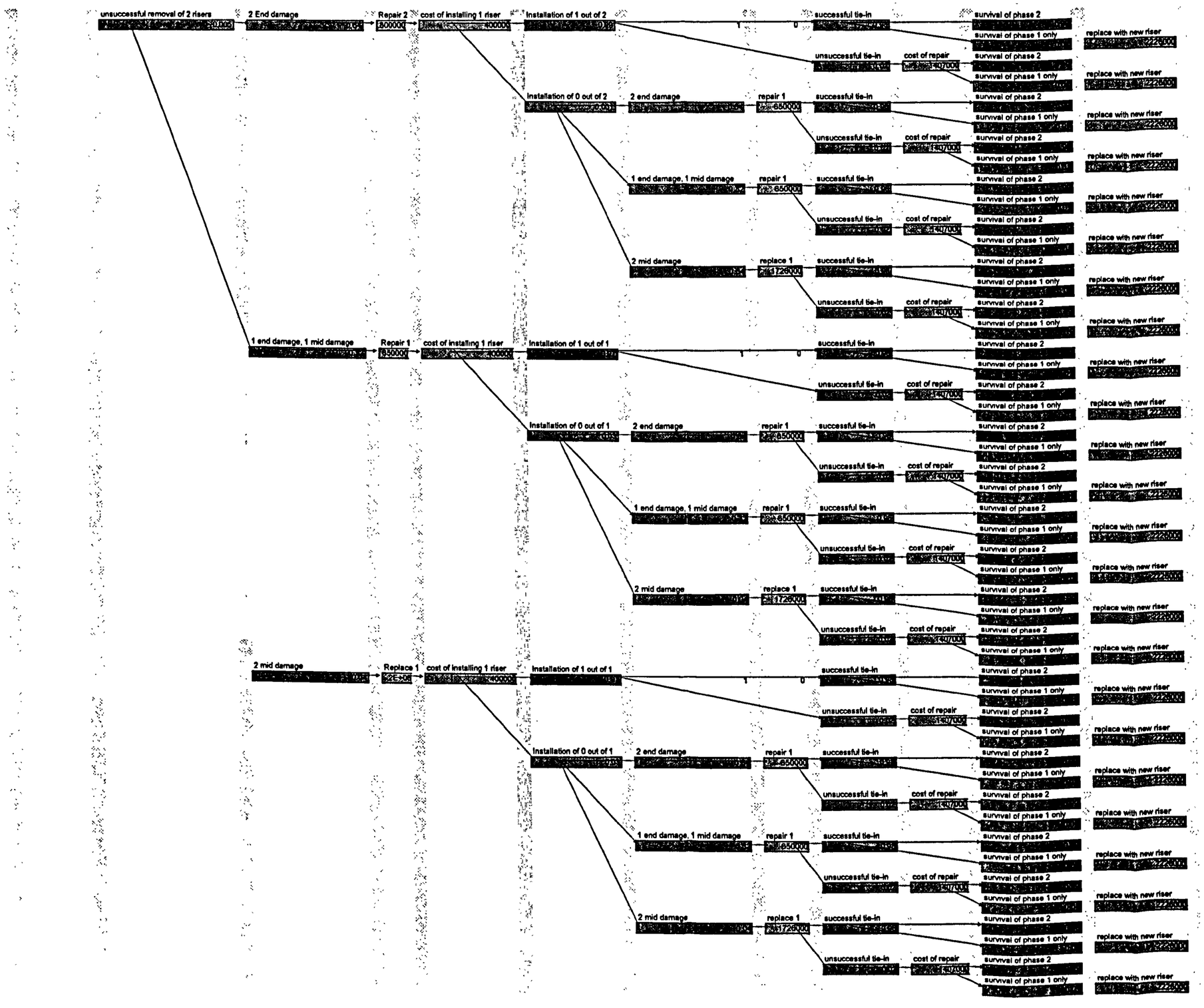

Gas Lift Risers Option 1
remove & reuse
successful removal
cost of installing 1 riser
Installation of 1 out of 2
successful tie-in
survival of phase 2
survival of phase 1 only
replace with new riser
unsuccessful tie-in
cost of repair
Installation of 0 out of 2
2 end damage
repair 1
1 end damage, 1 mid damage
2 mid damage
replace 1
unsuccessful removal of 1 riser
1 End damage
Repair 1
Mid damage
Replace 0
unsuccessful removal of 2 risers
2 End damage
Repair 2
Expected Cost
1375803.862

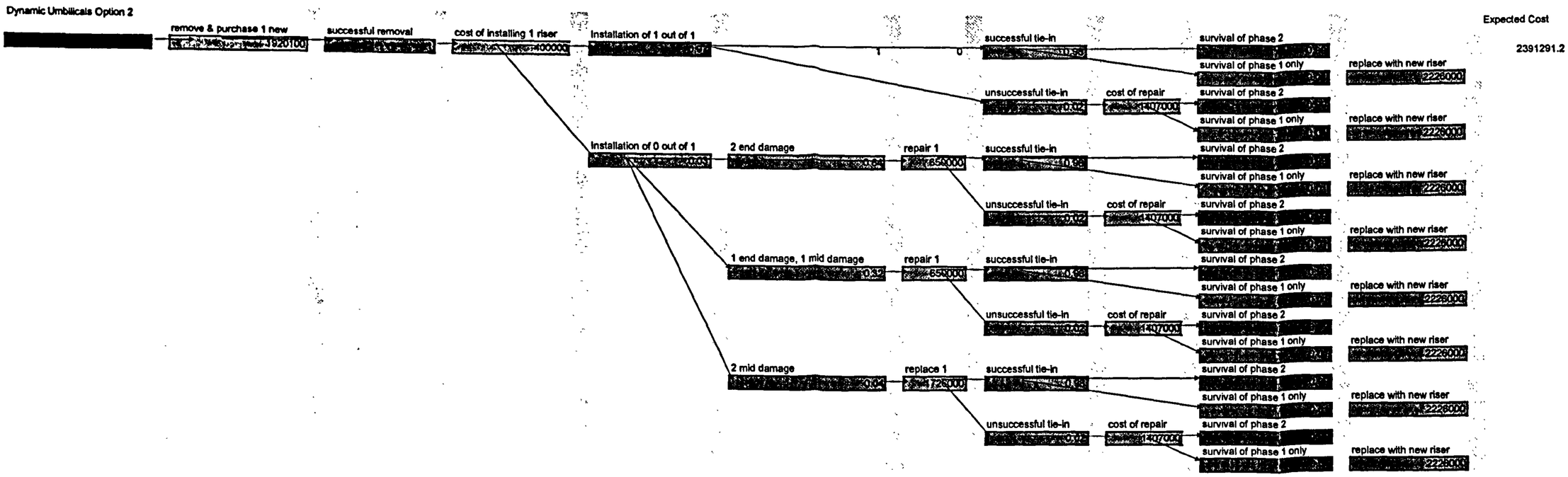

Gas Lift Risers Option 1
remove & reuse
successful removal
cost of installing 1 riser
Installation of 1 out of 2
successful tie-in
survival of phase 2
survival of phase 1 only
replace with new riser
unsuccessful tie-in
cost of repair
Installation of 0 out of 2
2 end damage
repair 1
1 end damage, 1 mid damage
2 mid damage
replace 1
unsuccessful removal of 1 riser
1 End damage
Repair 1
Mid damage
Replace 0
Installation of 1 out of 1
unsuccessful removal of 2 risers
2 End damage
Repair 2
Expected Cost
1375803.662

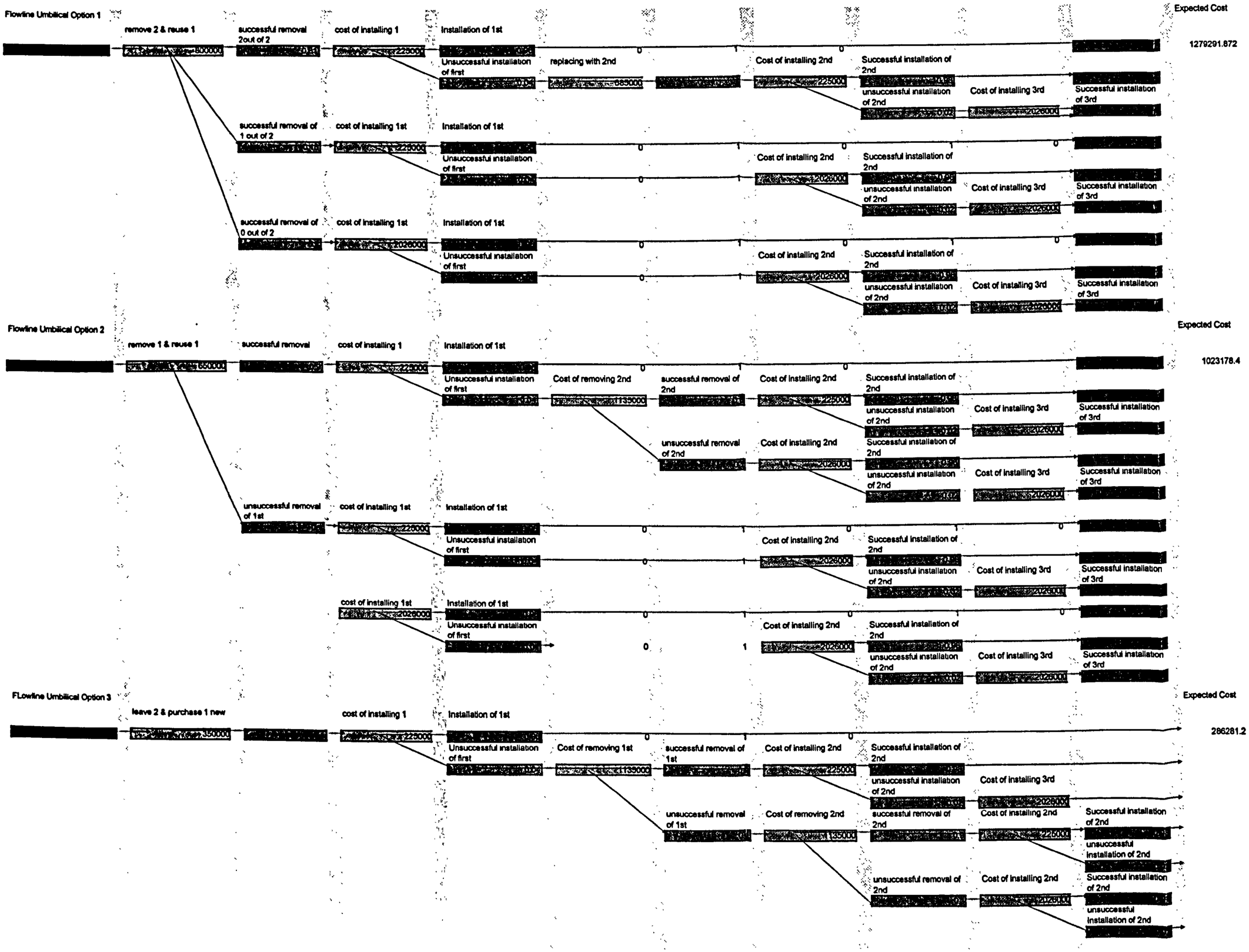

1 end damage, 1 mid damage
Repair 1
cost of installing 1 riser
Installation of 1 out of 1
1
0
Installation of 0 out of 2
2 end damage
repair 1
successful tie-in
unsuccessful tie-in
cost of repair
survival of phase 2
survival of phase 1 only
replace with new riser
1 end damage, 1 mid damage
repair 1
2 mid damage
replace 1
Installation of 0 out of 1
2 end damage
1 end damage, 1 mid damage
2 mid damage
2 mid damage
Replace 1
cost of installing 1 riser
Installation of 1 out of 1
Installation of 0 out of 1
2 end damage
1 end damage, 1 mid damage
2 mid damage

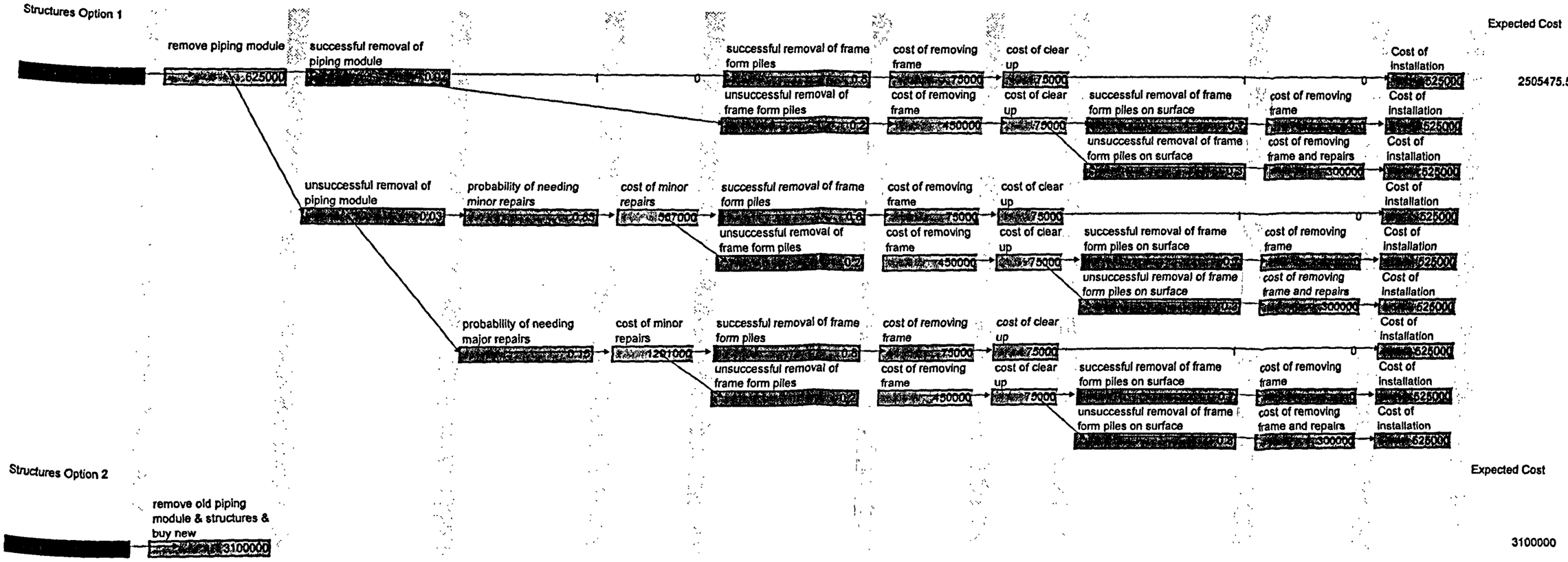

Gas Lift Risers Option 2
remove & purchase 1 new
2120000
successful removal
cost of installing 1 riser
400000
Installation of 1 out of 1
1
0
successful tie-in
survival of phase 2
survival of phase 1 only
replace with new riser
2226000
unsuccessful tie-in
cost of repair
1497000
Installation of 0 out of 1
2 end damage
repair 1
650000
1 end damage, 1 mid damage
2 mid damage
replace 1
1826000
Expected Cost
2595544.8


Dynamic Umbilicals Option 1
remove & reuse
successful removal
cost of installing 1 riser
Installation of 1 out of 2
successful tie-in
survival of phase 2
survival of phase 1 only
replace with new riser
unsuccessful tie-in
cost of repair
Installation of 0 out of 2
2 end damage
repair 1
1 end damage, 1 mid damage
2 mid damage
replace 1
unsuccessful removal of 1 riser
1 End damage
Repair 1
Mid damage
Replace 0
Installation of 1 out of 1
Installation of 0 out of 1
Expected Cost
1378206.599


unsuccessful removal of 2 risers
2 End damage
Repair 2
cost of installing 1 riser
Installation of 1 out of 2
successful tie-in
survival of phase 2
survival of phase 1 only
replace with new riser
unsuccessful tie-in
cost of repair
Installation of 0 out of 2
2 end damage
repair 1
1 end damage, 1 mid damage
2 mid damage
replace 1
1 end damage, 1 mid damage
Repair 1
cost of installing 1 riser
Installation of 1 out of 1
Installation of 0 out of 1
2 mid damage
Replace 1
cost of installing 1 riser
Installation of 1 out of 1
Installation of 0 out of 1


Dynamic Umbilicals Option 2
remove & purchase 1 new
1920100
successful removal
cost of installing 1 riser
400000
Installation of 1 out of 1
1
0
successful tie-in
survival of phase 2
survival of phase 1 only
replace with new riser
2226000
unsuccessful tie-in
cost of repair
407000
Installation of 0 out of 1
2 end damage
repair 1
650000
1 end damage, 1 mid damage
2 mid damage
replace 1
725000
Expected Cost
2391291.2


Flowline Umbilical Option 1
remove 2 & reuse 1
800000
successful removal 2out of 2
cost of installing 1
225000
Installation of 1st
Unsuccessful installation of first
replacing with 2nd
889000
Cost of installing 2nd
225000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
Successful installation of 3rd
successful removal of 1 out of 2
cost of installing 1st
225000
Installation of 1st
Unsuccessful installation of first
Cost of installing 2nd
2026000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
Successful installation of 3rd
successful removal of 0 out of 2
cost of installing 1st
2026000
Installation of 1st
Unsuccessful installation of first
Cost of installing 2nd
2026000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
Successful installation of 3rd
Expected Cost
1279291.872
Flowline Umbilical Option 2
remove 1 & reuse 1
650000
successful removal
cost of installing 1
225000
Installation of 1st
Unsuccessful installation of first
Cost of removing 2nd
1139000
successful removal of 2nd
Cost of installing 2nd
225000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
Successful installation of 3rd
unsuccessful removal of 2nd
Cost of installing 2nd
2026000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
Successful installation of 3rd
unsuccessful removal of 1st
cost of installing 1st
225000
Installation of 1st
Unsuccessful installation of first
Cost of installing 2nd
2026000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
Successful installation of 3rd
cost of installing 1st
2026000
Installation of 1st
Unsuccessful installation of first
Cost of installing 2nd
2026000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
Successful installation of 3rd
Expected Cost
1023178.4
FLowline Umbilical Option 3
leave 2 & purchase 1 new
350000
cost of installing 1
225000
Installation of 1st
Unsuccessful installation of first
Cost of removing 1st
1139000
successful removal of 1st
Cost of installing 2nd
225000
Successful installation of 2nd
unsuccessful installation of 2nd
Cost of installing 3rd
2026000
unsuccessful removal of 1st
Cost of removing 2nd
1139000
successful removal of 2nd
Cost of installing 2nd
225000
Successful installation of 2nd
unsuccessful installation of 2nd
unsuccessful removal of 2nd
Cost of installing 2nd
225000
Successful installation of 2nd
unsuccessful installation of 2nd
Expected Cost
286281.2


Structures Option 1
remove piping module
625000
successful removal of piping module
0.97
successful removal of frame form piles
0.8
cost of removing frame
75000
cost of clear up
75000
Cost of installation
625000
unsuccessful removal of frame form piles
0.2
cost of removing frame
450000
cost of clear up
75000
successful removal of frame form piles on surface
0.2
cost of removing frame
Cost of installation
625000
unsuccessful removal of frame form piles on surface
0.8
cost of removing frame and repairs
300000
Cost of installation
625000
unsuccessful removal of piping module
0.03
probability of needing minor repairs
0.65
cost of minor repairs
567000
successful removal of frame form piles
0.8
cost of removing frame
75000
cost of clear up
75000
Cost of installation
625000
unsuccessful removal of frame form piles
0.2
cost of removing frame
450000
cost of clear up
75000
successful removal of frame form piles on surface
0.2
cost of removing frame
Cost of installation
625000
unsuccessful removal of frame form piles on surface
0.8
cost of removing frame and repairs
300000
Cost of installation
625000
probability of needing major repairs
0.35
cost of minor repairs
1201000
successful removal of frame form piles
0.8
cost of removing frame
75000
cost of clear up
75000
Cost of installation
625000
unsuccessful removal of frame form piles
0.2
cost of removing frame
450000
cost of clear up
75000
successful removal of frame form piles on surface
0.2
cost of removing frame
Cost of installation
625000
unsuccessful removal of frame form piles on surface
0.8
cost of removing frame and repairs
300000
Cost of installation
625000
Expected Cost
2505475.5
Structures Option 2
remove old piping module & structures & buy new
3100000
Expected Cost
3100000

APPENDIX 3 A SUMMARY OF THE COMPUTATIONAL PROCEDURE OF FORM/SORM METHODS

In order to assess the reliability of a structural component, a limit-state or a set of limit-states is identified which determine the performance of the component. These limit-states could be either ultimate limit-states or serviceability limit-states. For each limit-state a reliability analysis is carried out to determine the probability that this limit-state will not be reached. The reliability of the structural component is then defined as the probability that none of the limit-states will be reached within the specified service life of the structure. Reliability formulation for a single limit-state (sometimes referred to as a "failure element") of a component is presented below.

The first step in a reliability analysis is to identify a set of basic random (or uncertain) variables that influence the failure mode or limit-state under consideration. Let in the following $\bar{X} = (X_1, X_2, \ldots, X_n)$ represent such a vector of n "basic variables".

Next, a "safety margin" expression is formulated in terms of the basic variables as (see Madsen et al (1986)).

$$M = g(\bar{X}) = g(X_1, X_2, \ldots, X_n) \qquad \text{(A-1)}$$

Where M is the safety margin. The equation is formulated in such a way that $g(\bar{x})>0$ implies that the component is in the "safe domain" and $g(\bar{x})<0$ indicates that the component is in the "failure domain". The function $g(.)$ is referred to as the "limit-state function" and it relates the basic variables to the safety margin. $g(\bar{x})=0$ defines an $(n-1)$ dimensional surface dividing the safe domain and the failure domain and is called the "failure surface" or "limit-state surface".

The reliability or the probability that the limit-state will not be reached is then expressed as

$$R = 1 - p_f = 1 - P[M \leq 0] = 1 - \int f_{\bar{X}}(\bar{x})\overline{dx} \qquad \text{(A-2)}$$

where $f_{\bar{x}}(.)$ is the joint probability density function of the n basic variables and p_f denotes probability of failure. The n-dimensional integral is defined over the failure domain.

The reliability as expressed in Eq.A-2 can be evaluated using one of the three following approaches:

1. Numerical integration;
2. Monte-Carlo simulation;
3. 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. These methods are also known in some circles as "advanced Level II methods". These methods will be used in the current study and are summarised below.

The vector of basic variables $\underline{X}$, described by the joint probability density function $f_{\underline{x}}$, is first transformed to a standard normal space (also called as *"u-space"*), in which the variables are statistically independent and each variable is normally distributed with zero mean value and unit standard deviation. This transformation maps the failure surface $g(\underline{x})=0$ in the original space to a surface $g_{\underline{u}}(\underline{u})=0$ in the u-space, see Fig.A-1. Using an iterative technique, the point on the failure surface that is closest from the origin in the transformed space is located. This point is called as the "design point" or the "most-likely failure point". In the First Order Reliability Method (FORM), the actual non-linear failure surface is approximated by a hyperplane having the same gradients as the actual failure surface at the design point. In the Second Order Reliability Method (SORM), the failure surface is approximated by a quadratic surface with the same curvatures as the actual failure surface at the design point. The integral over the failure domain bounded by a hyperplane or a quadratic surface can then be evaluated using simple analytical expressions.

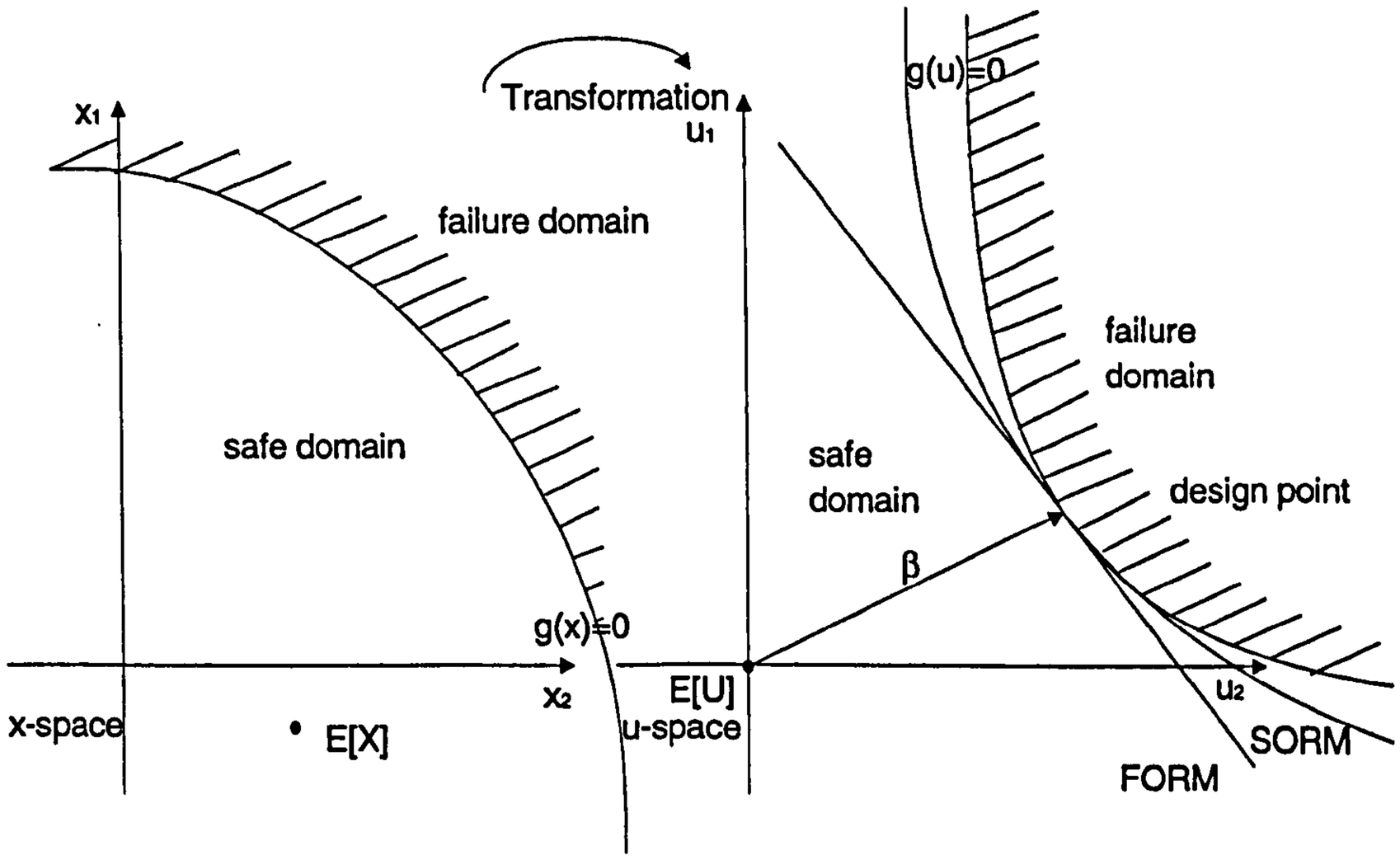


Figure A-1: Illustration of FORM and SORM

In reliability literature it is now more common to use the term "reliability index β" instead of the probability of failure. Reliability index is the distance from the origin to the design point in the *u*-space. It is evaluated as

$$\beta = \left[\sum_{i=1}^{n} u_i^{*2} \right]^{1/2} \qquad \text{(A-3)}$$

where u_i^* are the coordinates of the design point.

The reliability index is formally related to p_f through

$$p_f = \Phi(-\beta) \qquad \text{(A-4)}$$

where $\Phi(.)$ is the standard normal cumulative distribution function. This relationship is exact when the basic variables are normally distributed and the limit-state function is linear. In other cases it is only approximate.

In the special case of a linear limit-state function and normal probability distributions for basic variables, the reliability index can be evaluated very easily

$$\beta = \frac{\mu_M}{\sigma_M} \qquad \text{(A-5)}$$

where M is the safety margin from Eq.A-1.

In addition to the reliability index, a FORM/SORM approach also provides what are known as "sensitivity factors", expressed for each basic variable as

$$\alpha_i = -\frac{\partial \beta}{\partial u_i}\Big|_{u^*} \qquad \text{(A-6)}$$

The gradients are evaluated at the design point u^*. The vector $\bar{\alpha}$ represents a unit vector normal to the failure surface at the design point. The numerical value of α_i is thus a measure of the sensitivity of the reliability index to uncertainties in the variable U_i.

APPENDIX 4 GRAPHS SHOWING THE SENSITIVITY RESULTS FOR EACH FAILURE MODE. (CASE STUDY 2)

A1.1 Introduction

Reliability analysis was carried out for one specific geometrical type of reinforced concrete viaduct crossbeam for the limit-states of flexure, shear and bond. For each limit state, the most critical cross-section position along the crossbeam was selected.

For the flexure limit state, the cross-section selected was close to the column of the middle span that was in hogging. For the shear limit state, a cross-section of the crossbeam in the middle span was chosen for the analysis. For the bond limit state, the cross-section selected was towards the centre of the middle span from the column supporting the middle span.

For flexure, shear and bond limit-states, the analysis was performed for three conditions of the crossbeam: (i) as-built condition (ii) present condition with some loss of strength due to corrosion of reinforcement and delamination, and (iii) future condition with further corrosion of reinforcement and delamination in the future years. For the bond limit state, analyses were carried out for differing degrees of initial delamination in the present condition. In addition, a case was analysed assuming that the crossbeam was fully delaminated in its present condition. The results from these analyses are presented in the following. Since the input distributions were not accurate at this stage for all the variables (especially loading and deterioration), the results of reliability indices are not presented and only the sensitivity factors are provided. It is believed that the results of sensitivity factors will not change significantly when the input distributions are revised.

A1.2 Flexure Limit State

APPENDIX 5 As-built condition

The results of sensitivity factors show the relative importance (expressed as a percentage) of the uncertainty in each variable to the reliability index. The sensitivity results for flexure, for the as-built condition of the crossbeam, shown in Figure A-2, revealed that the reliability index is very sensitive to the uncertainty in bending moment due to the live load and the impact factor. The yield strength of longitudinal reinforcement and the uncertainties in the models used for load effect analysis and capacity of the component were also found to be very important. Uncertainty in other variables, such as the concrete cube strength, effective depth, diameter of longitudinal steel and dead load were not seen to have a significant influence on the probability of failure.

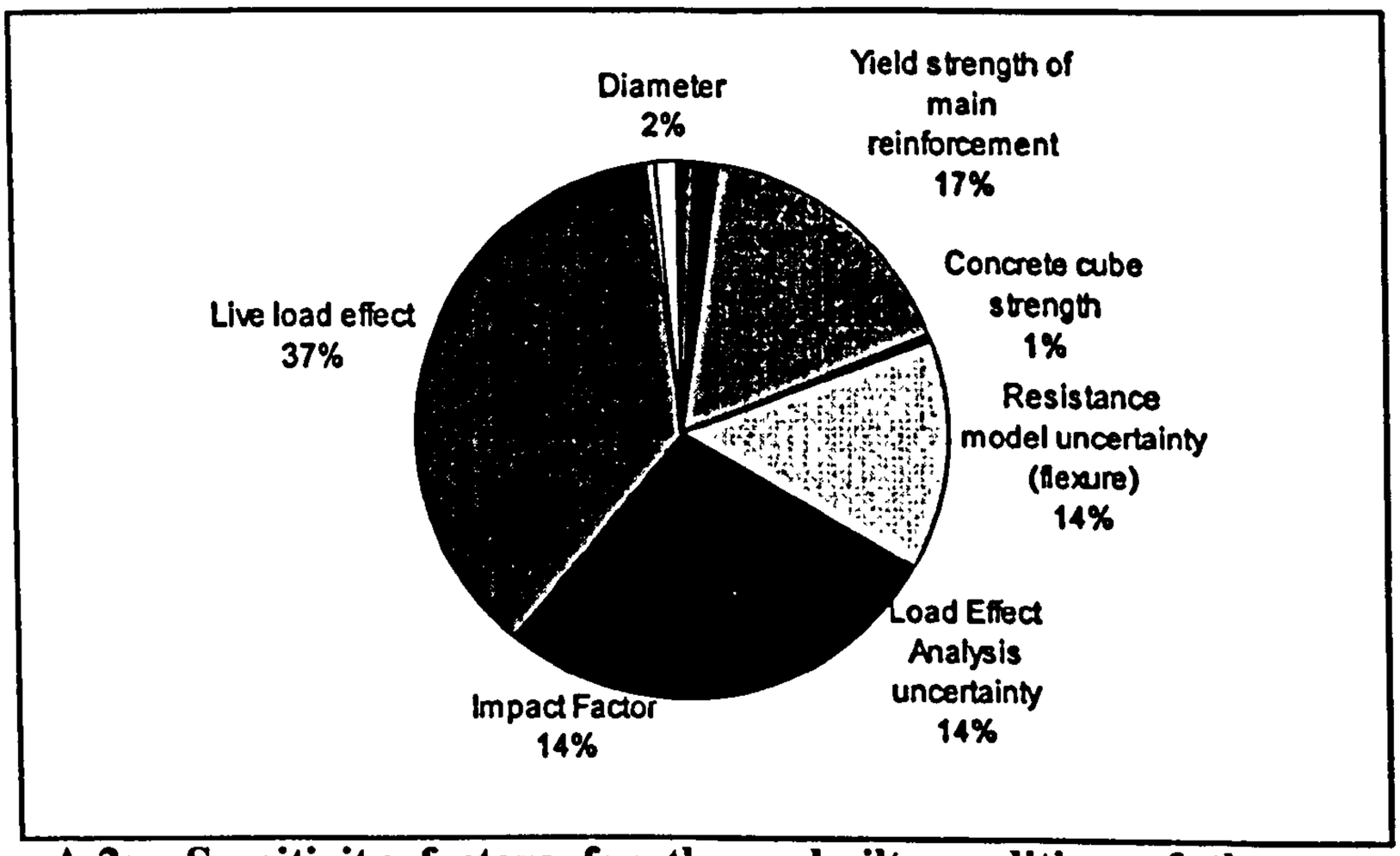


Figure A-2: Sensitivity factors for the as-built condition of the crossbeam - FLEXURE LIMIT STATE

The elasticities of the variables' mean values represent the change in reliability index due to a small change in the variable mean value. The flexure case results, shown in Figure A-3, show that the mean values of bar diameter, longitudinal reinforcement yield strength and section effective depth were very important. The mean values of the analysis and capacity model parameters were also important. The elasticities are positive for those variables for which an increase in the mean value will increase the reliability of the component and will be negative for the other variables.

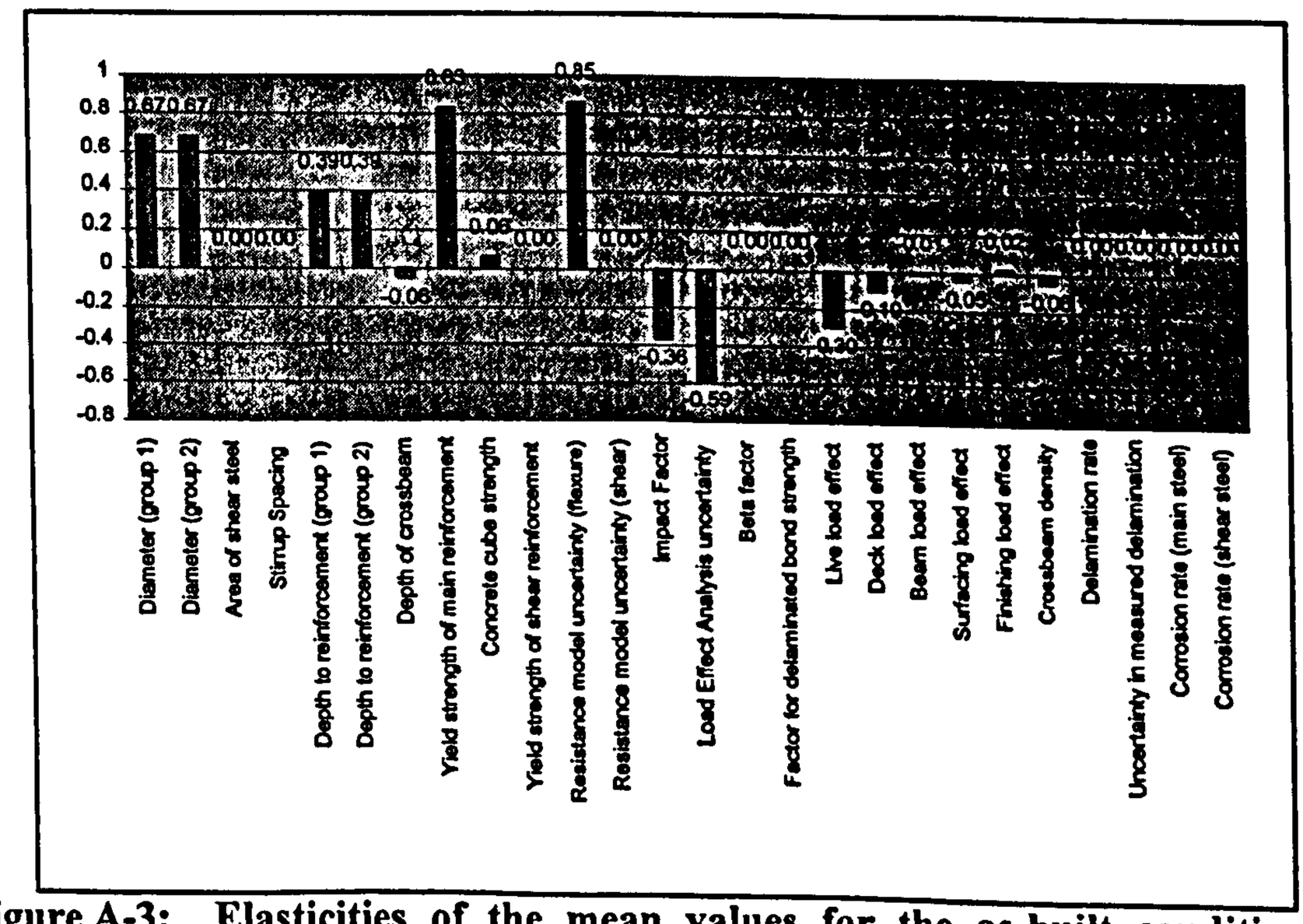


Figure A-3: Elasticities of the mean values for the as-built condition of the crossbeam - FLEXURE LIMIT STATE

The elasticities of standard deviation for the bending limit-state represent the change in reliability index due to a small change in a variable's standard deviation. The elasticities for all variables are negative because increasing the standard deviation of any variable will decrease the reliability of the component. The flexure case results show that the standard deviations of live load bending moment, impact factor, yield strength of reinforcement and model uncertainty parameters were very important for reliability.

The elasticities of standard deviation are shown in Figure A-4. These were much lower than the elasticities of the mean values of these variables. This implied that it is more important to determine the mean values of the parameters accurately than the standard deviation. Fortunately, in the context of yield strength, the mean value can be determined accurately using a smaller number of samples than would be required to evaluate the standard deviation to the same level of accuracy. Using statistical analysis techniques the number of samples required for a given level of confidence in the estimation of the mean and the standard deviation can be calculated.

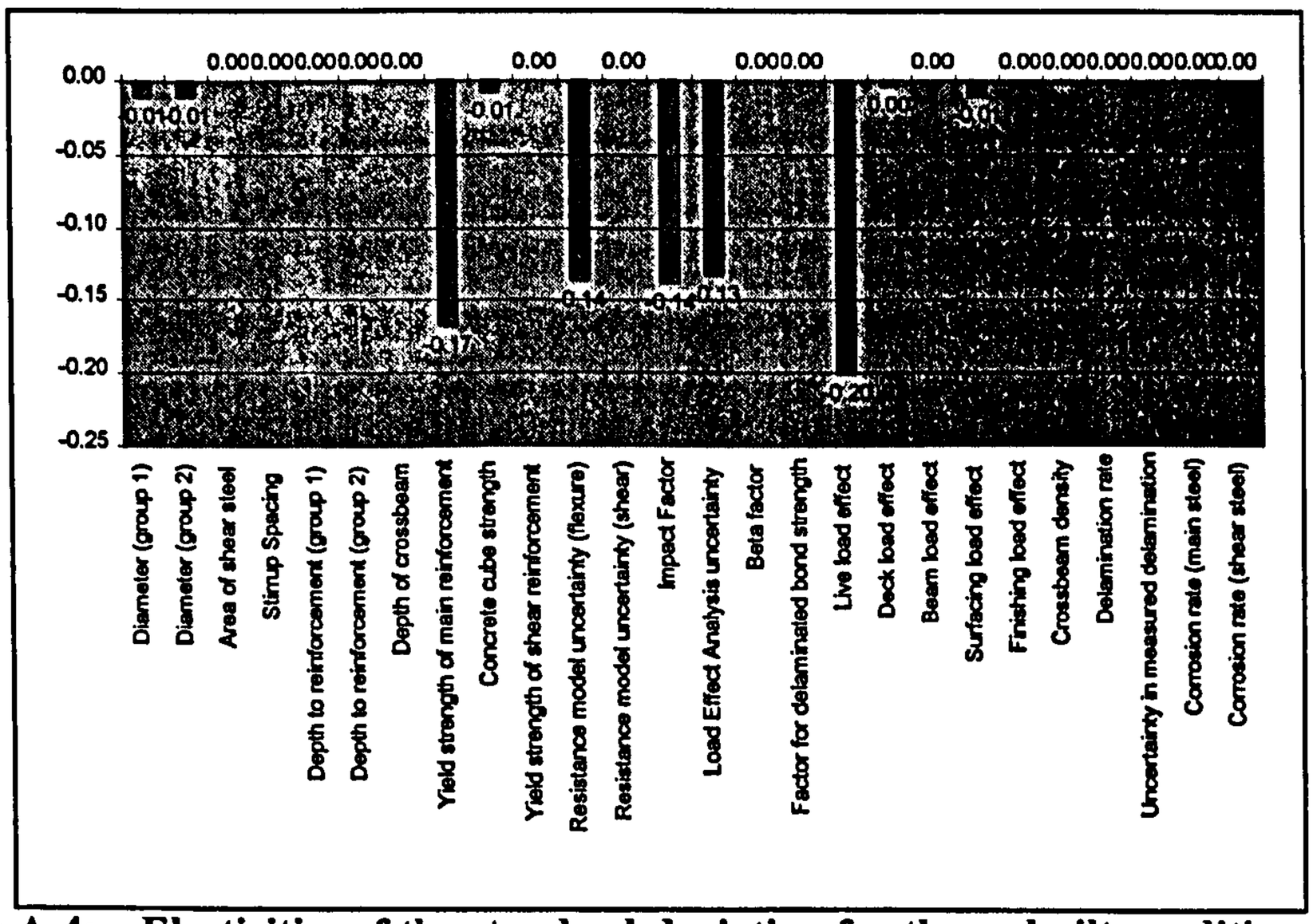


Figure A-4: Elasticities of the standard deviation for the as-built condition of the crossbeam - FLEXURE LIMIT STATE

APPENDIX 6 Present condition

For the present condition, the reliability of the crossbeam was calculated assuming that the longitudinal reinforcement had undergone some corrosion damage. The corrosion of longitudinal reinforcement over time was calculated using the deterioration model given in Chapter 6, assuming that corrosion initiated in 1986. The loss of concrete in the compressive zone was not included as it had a marginal influence on bending capacity. A "Base Case" analysis was carried out for a high corrosion rate with -390mV half-cell value. Additional parametric studies were then carried out for lower half-cell potential.

Figure A-5 shows the sensitivity factor results from the Base Case analysis. The corrosion coefficient uncertainty used to calculate the loss of reinforcement area was the most dominant variable for a high corrosion rate. The other variables are insignificant.

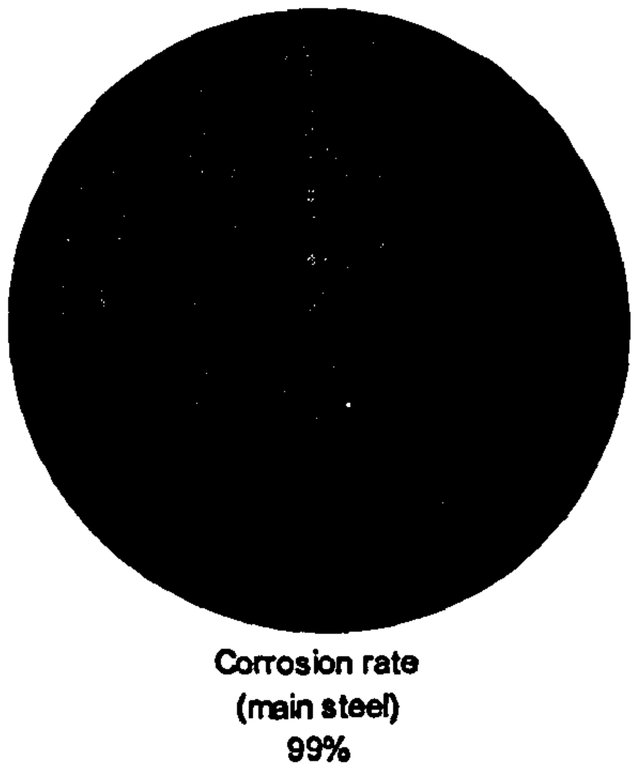


Figure A-5: Sensitivity Factors for Present Condition of the Crossbeam (High Corrosion Rate) - FLEXURE LIMIT STATE

Figure A-6 shows the mean value elasticities for the flexure limit state. The bar diameter and corrosion coefficient mean values dominate. The longitudinal reinforcement yield strength and the analysis and capacity model parameters are also important. At first glance, there may be surprise that the elasticity of the corrosion rate is positive, since an increase in the mean should result in a decrease in the reliability index. However since the mean value of the corrosion rate is negative, the ratio, $\partial\beta/\partial\mu_i$ is positive.

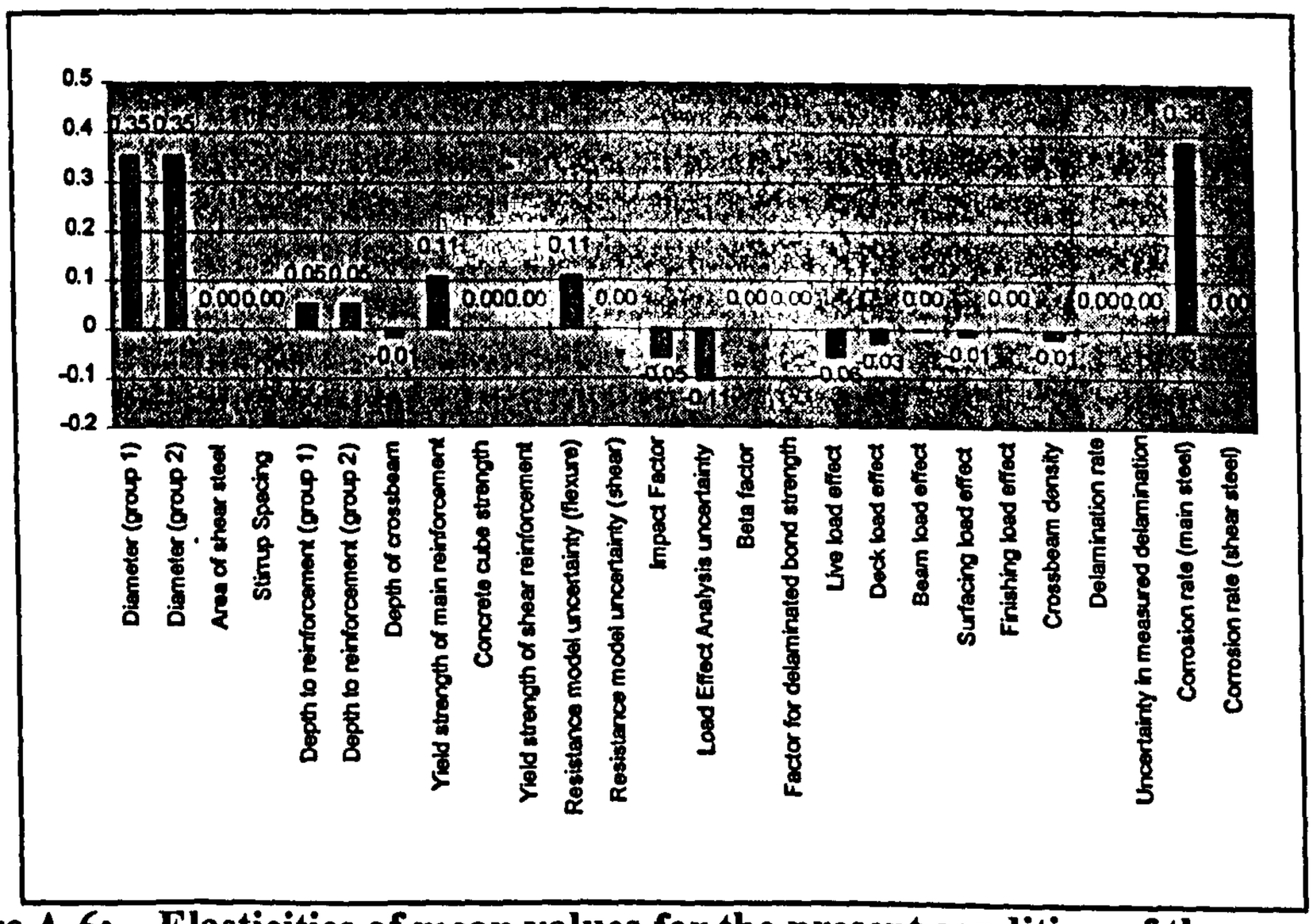


Figure A-6: Elasticities of mean values for the present condition of the crossbeam (high corrosion rate) - FLEXURE LIMIT STATE

The elasticities of the variables' standard deviation, in Figure A-7, showed that the corrosion coefficient variability dominated the crossbeam reliability under bending.

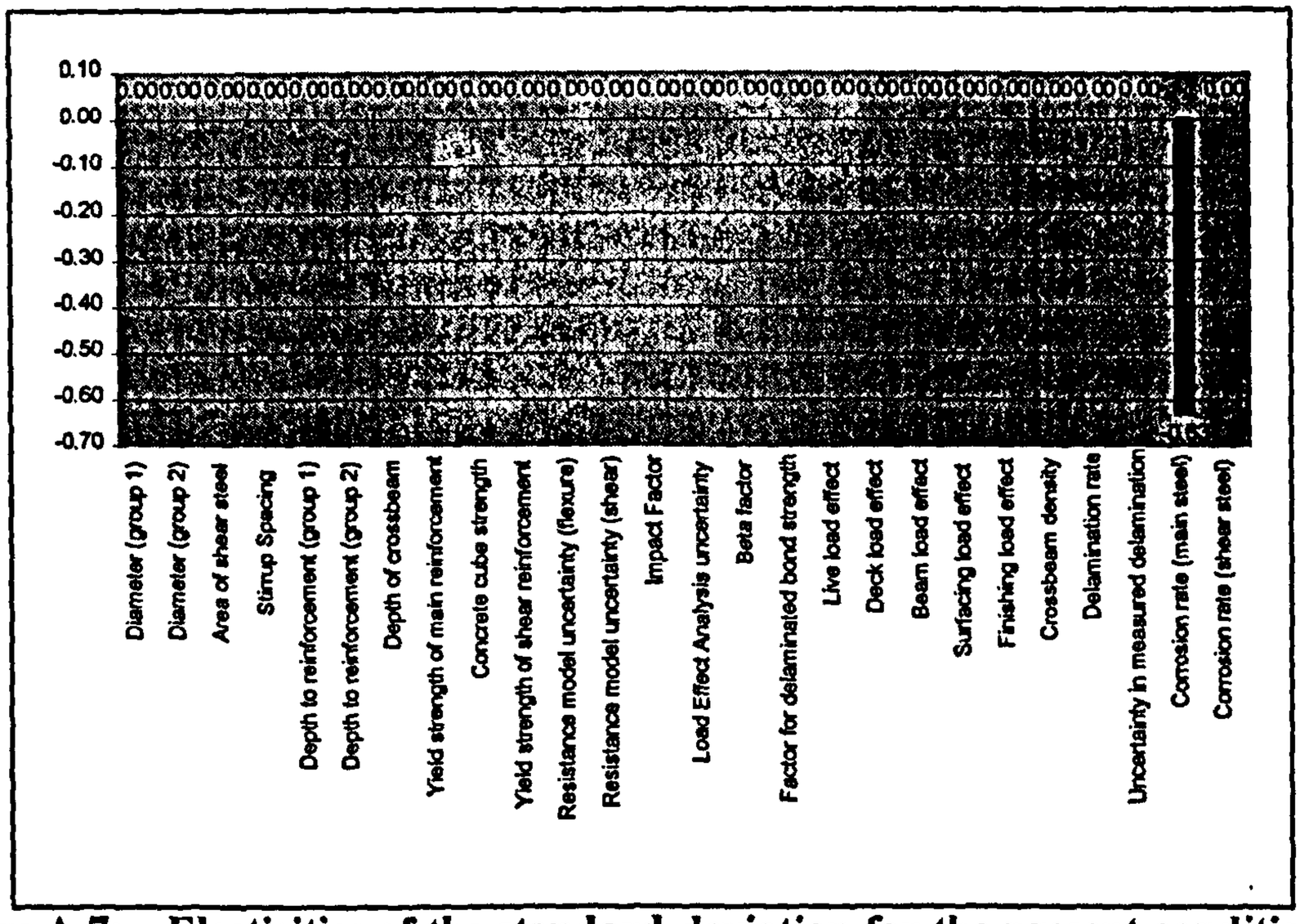


Figure A-7: Elasticities of the standard deviation for the present condition (high corrosion rate) - FLEXURE LIMIT

The effect of different corrosion rates on crossbeam reliability is evaluated through reliability analyses for half-cell measurements ranging from (low corrosion rate) to -390mV (high). Figure A-8 shows the sensitivity results for the -290mV case. These factors are the same as for the as-built case, i.e. corrosion parameters are not important.

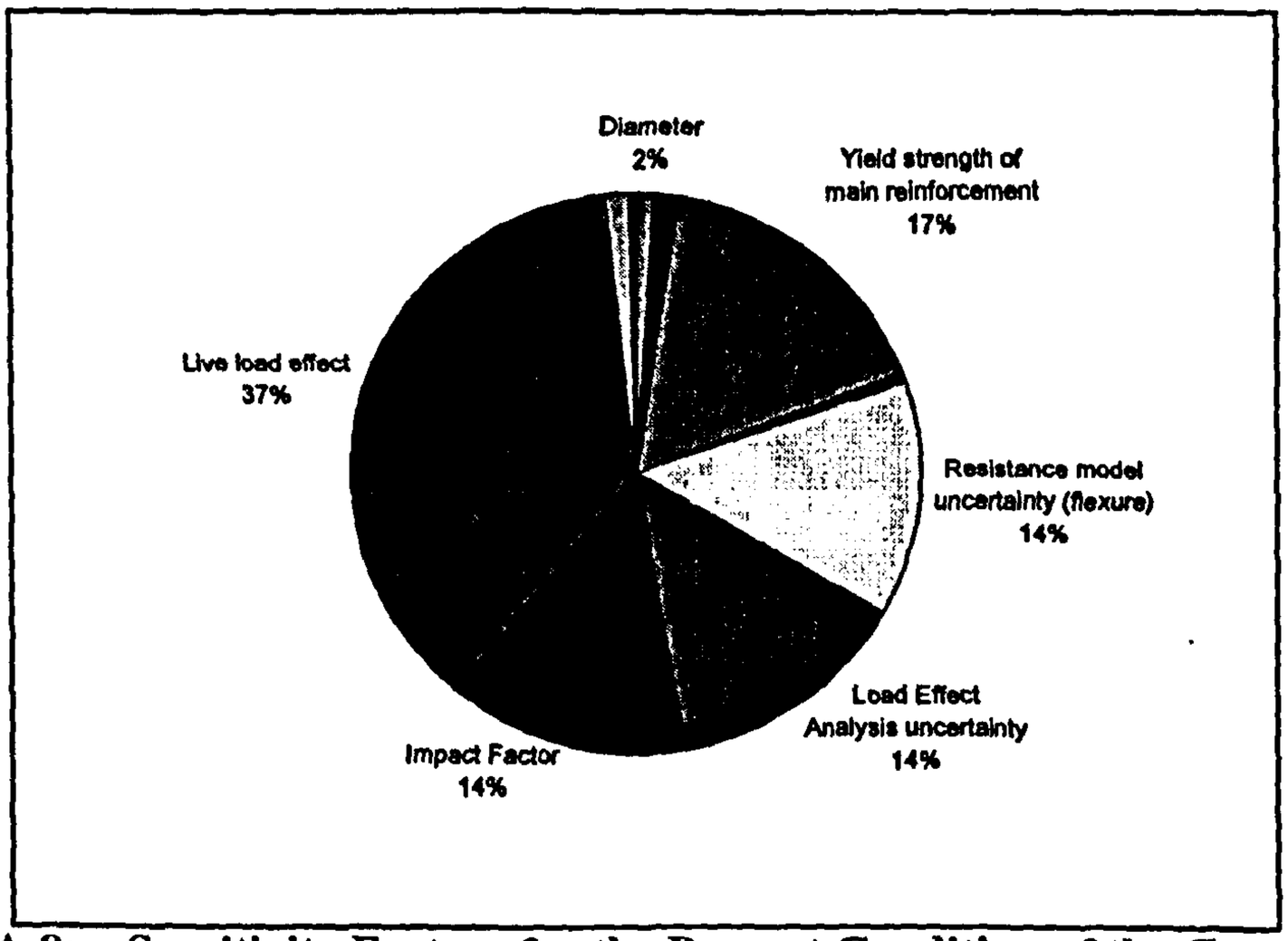


Figure A-8: Sensitivity Factors for the Present Condition of the Crossbeam (Low Corrosion Rate) - FLEXURE LIMIT STATE

APPENDIX 7 Future condition

The reliability of the crossbeam was also calculated at different points in time in the future. The corrosion of longitudinal reinforcement over time was calculated using the deterioration model given in Chapter 6, assuming that corrosion initiated in 1986. Again, the loss of concrete was not modelled.

The results of sensitivity factors for the bending case are shown in Figure A-9. These correspond to a "high" rate of corrosion and show that the uncertainty in the corrosion coefficient dominates the reliability of a crossbeam as in the case of the present condition. It was however, found that if the rate of corrosion was "low", the sensitivities were similar to those of the as-built condition.

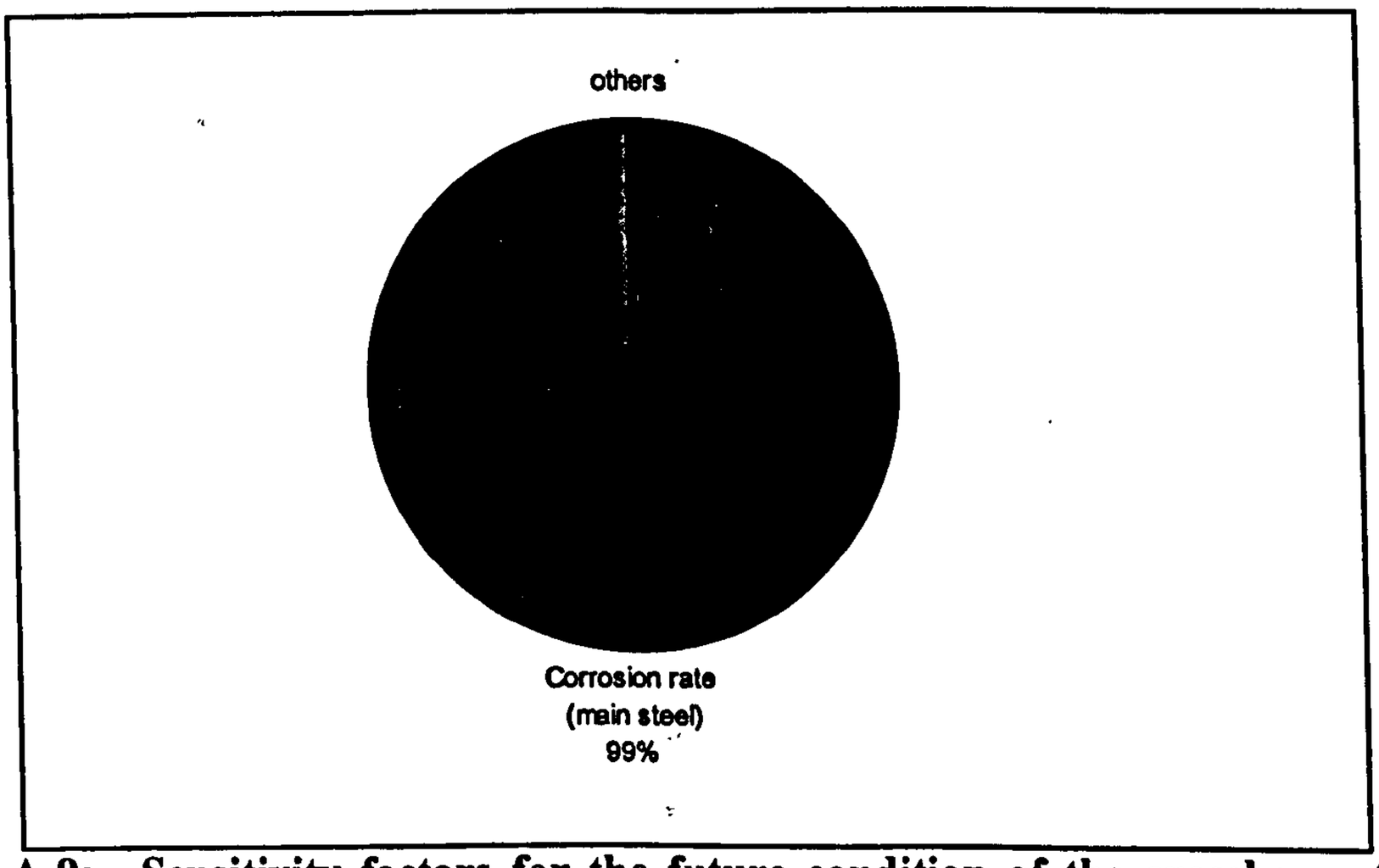


Figure A-9: Sensitivity factors for the future condition of the crossbeam (high corrosion rate) - FLEXURE LIMIT STATE

The results of elasticities of the mean and the standard deviation showed a similar trend as was evident from the sensitivity factors. The elasticities were in general similar to the corresponding values for the present condition. These results have not, therefore, been shown here.

Parametric reliability analyses were also carried out to study the variation in reliability due to deterioration over time. The results for "low", "medium" and "high" rates of corrosion were assessed and are shown in Figure A-10. These results revealed that the reliability decreased significantly with time in the first 5 to 10 years after the initiation of corrosion. The decrease in reliability was more pronounced only for the "medium" and "high" corrosion rate cases and showed almost no reduction when the corrosion rate was "low". These results, however, do not imply that the reliability will not decrease if the half-cell value is more positive than -250. This depends to some extent on the initial capacity ratio of the crossbeam and the proportion of live load carried by the crossbeam.

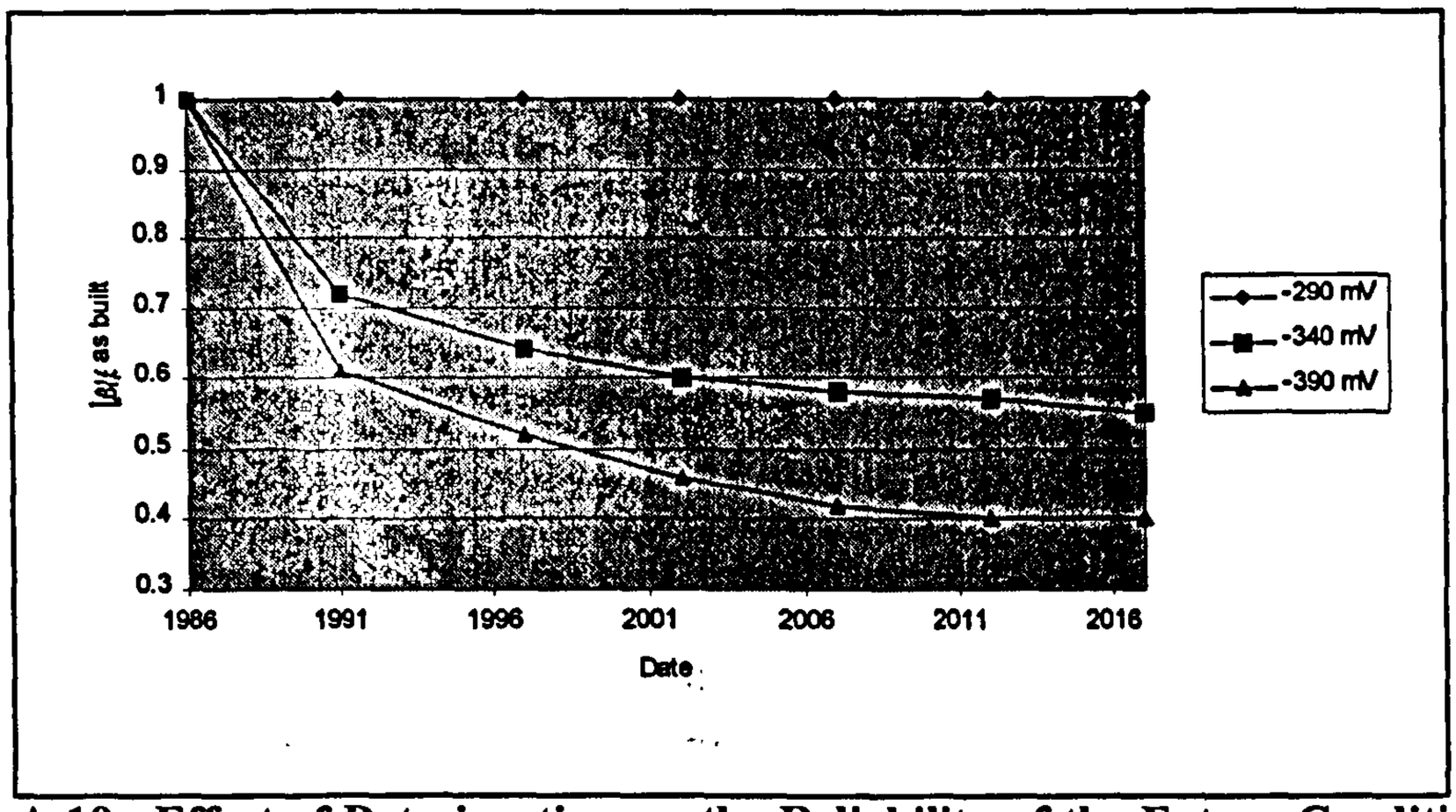


Figure A-10: Effect of Deterioration on the Reliability of the Future Condition of the Crossbeam - FLEXURE LIMIT STATE

A1.3 Shear Limit State

APPENDIX 8 As-built condition

The results of the sensitivity factors for the as-built condition of the crossbeam, for the limit-state of shear, as in Figure A-11.

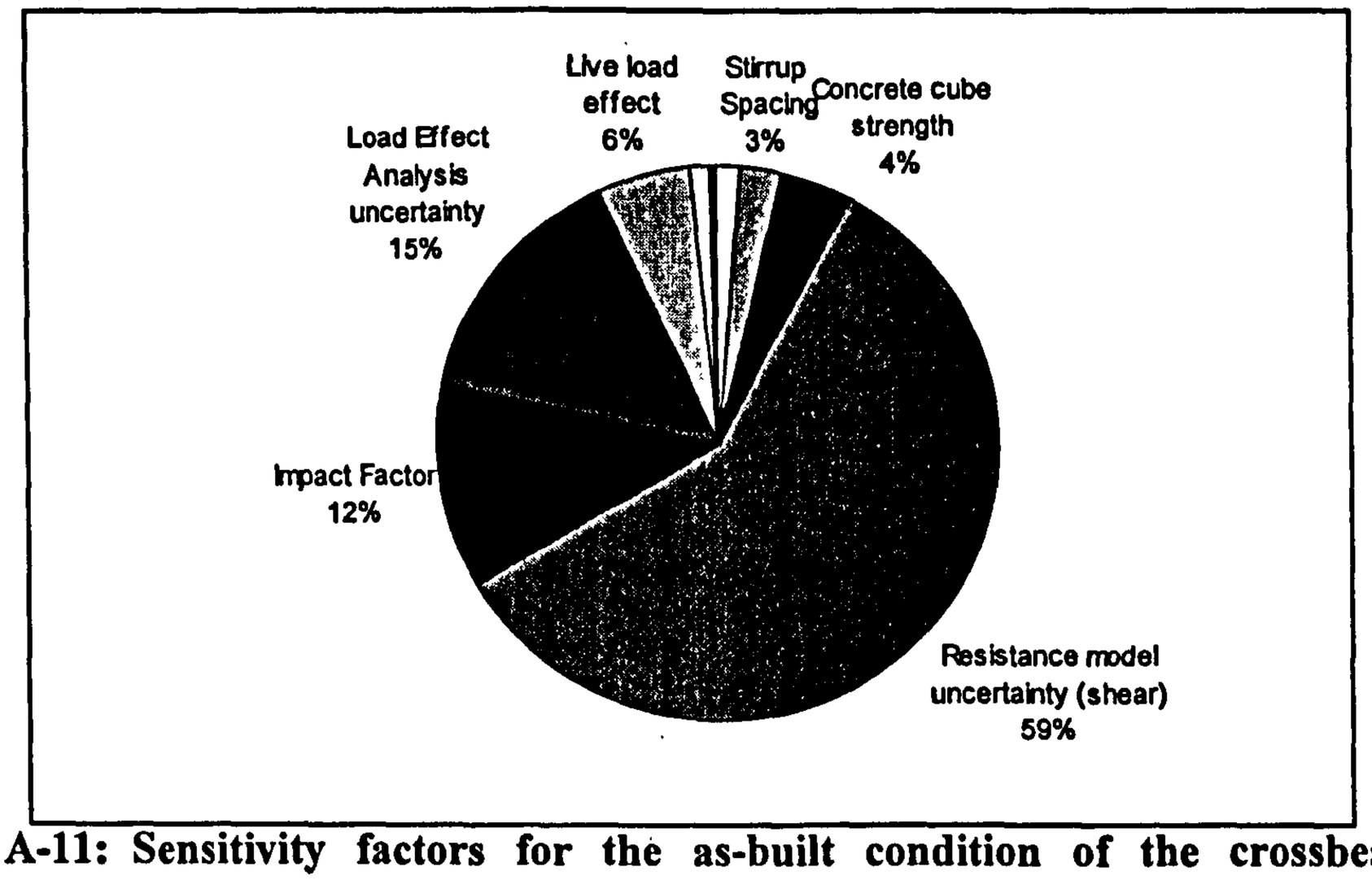


Figure A-11: Sensitivity factors for the as-built condition of the crossbeam SHEAR LIMIT STATE

The elasticities of the mean values of the variables, shown in Figure A-12, were high for the mean values of the resistance model and analysis model compared to other variables. Also it is worth noting that these parameters were significantly more important for shear than for bending.

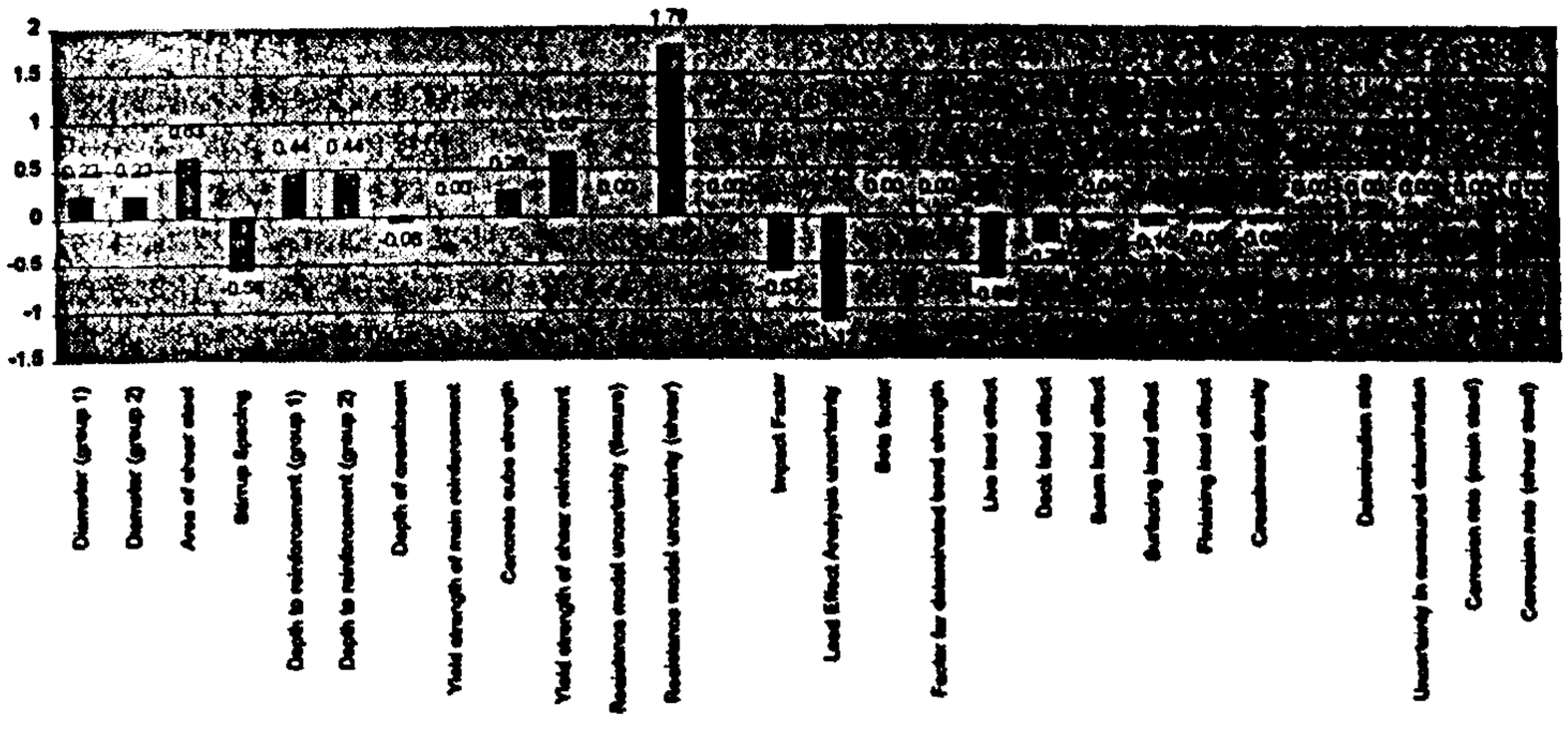


Figure A-12: Elasticities of the mean values for the as-built condition of the crossbeam - SHEAR LIMIT STATE

The elasticities of standard deviation are shown in Figure A-13. It can be seen that the elasticity of the resistance model was much higher than all the other variables. The elasticities of the standard deviation were in general considerably lower than the elasticities of the mean values.

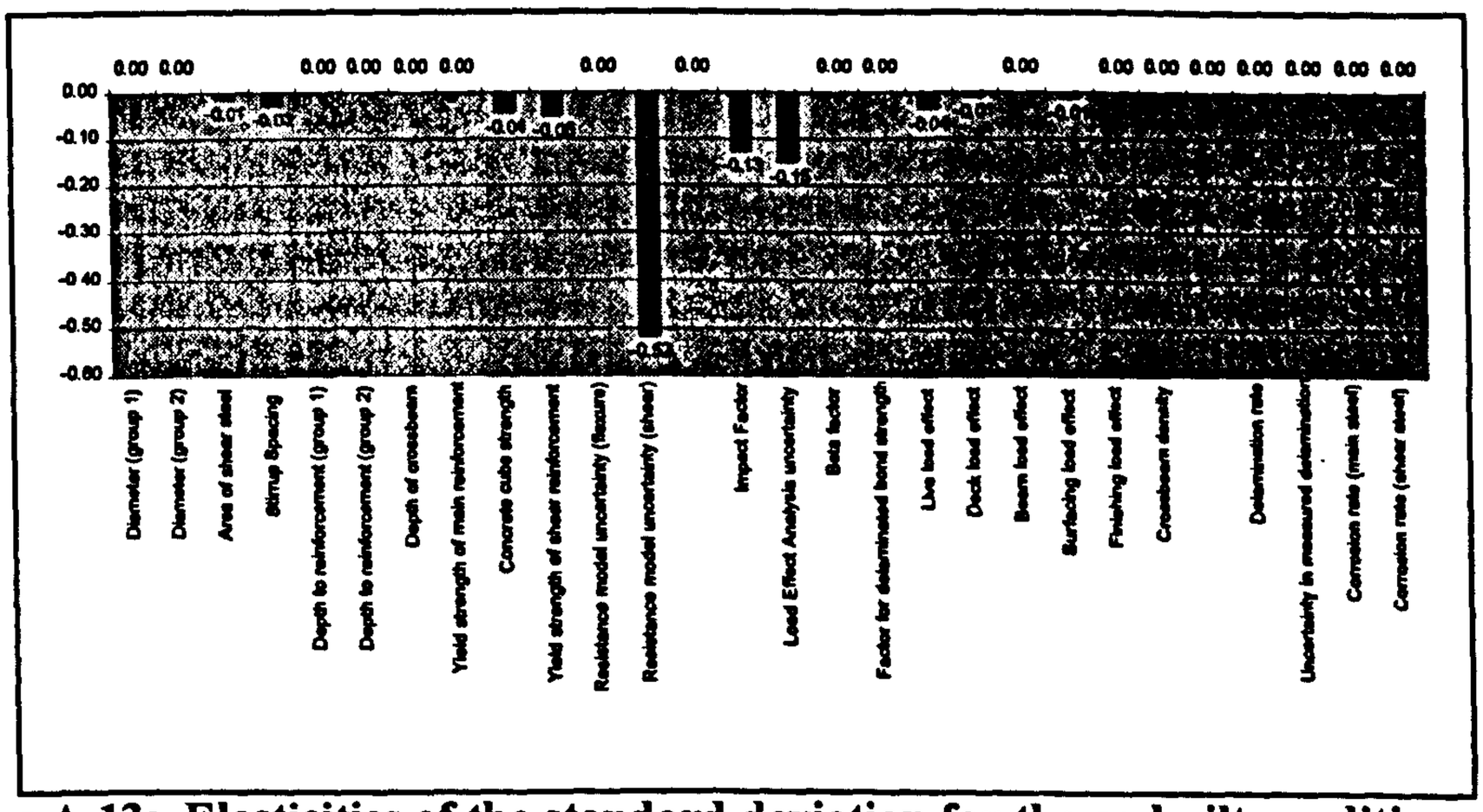


Figure A-13: Elasticities of the standard deviation for the as-built condition of the crossbeam - SHEAR LIMIT STATE

APPENDIX 9 Present condition

For the present condition, the corrosion of longitudinal and shear reinforcement over time was calculated using the deterioration model given in Chapter 6, assuming that corrosion initiated in 1986. The loss of concrete section in the compressive zone was not included. A "Base Case" analysis was carried out for a high corrosion rate determined by a -390mV half-cell potential.

The results of sensitivity factors from the Base Case analysis, shown in Figure A-14, showed that the uncertainty in corrosion rate for shear had a dominating influence on reliability for a high corrosion situation. The contribution from other variables became insignificant.

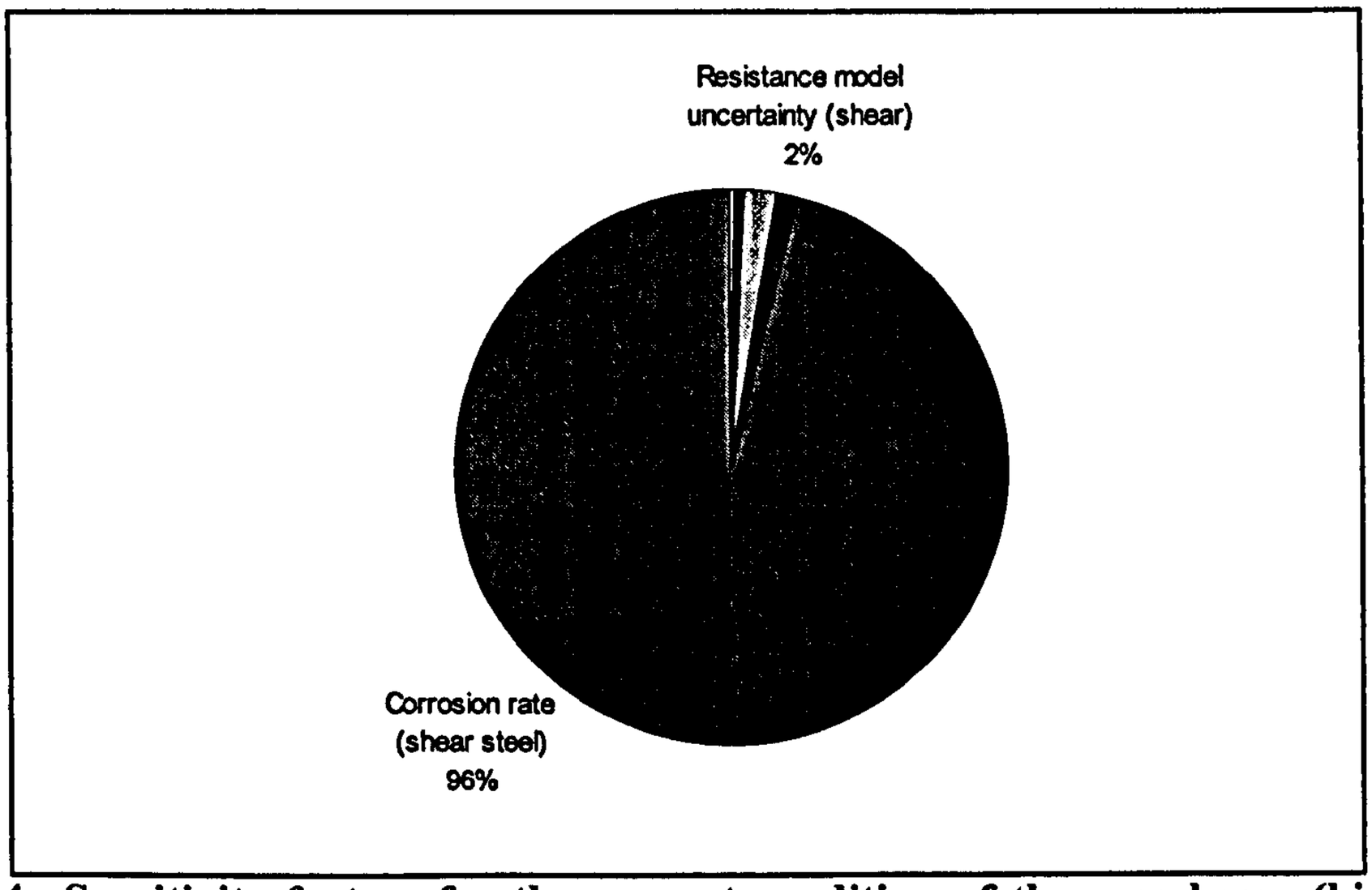


Figure A-14: Sensitivity factors for the present condition of the crossbeam (high corrosion) - SHEAR LIMIT STATE

The elasticities of the mean values, given in Figure A-15, were high for the mean values of the resistance model and analysis model compared to other variables. Also significant were the mean values of the area of shear steel and the corrosion rate of shear steel.

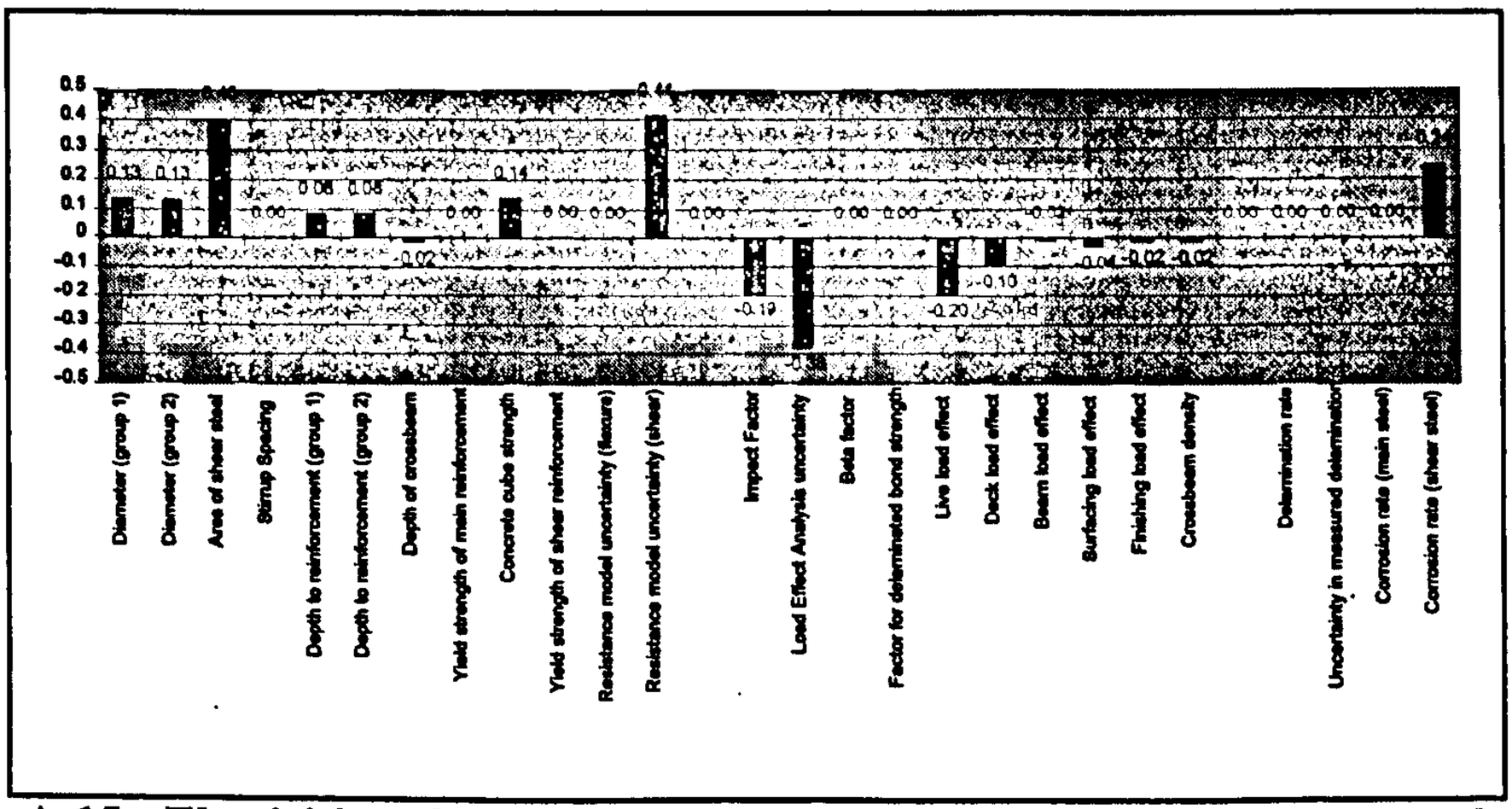


Figure A-15: Elasticities of mean values for the present condition of the crossbeam (high corrosion rate) - SHEAR LIMIT STATE

The elasticities of the variable standard deviations, in Figure A-16, showed that the standard deviation of shear steel corrosion rate dominates the uncertainty importances.

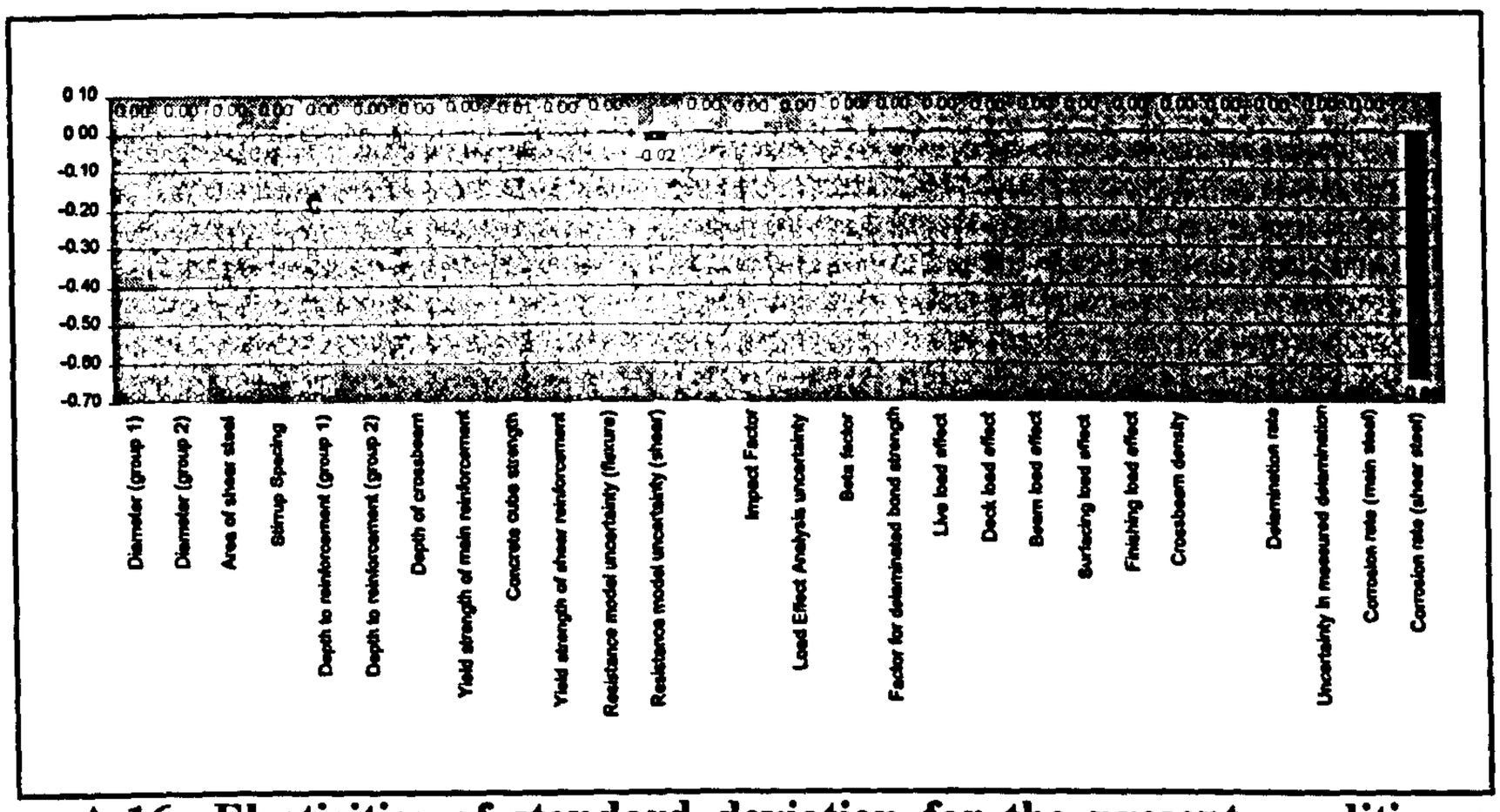


Figure A-16: Elasticities of standard deviation for the present condition of the crossbeam (high corrosion rate) - SHEAR LIMIT STATE

The effect of different corrosion rates on the crossbeam reliability was studied by carrying out analyses for half cell values from -290mV (low) to -390mV (high). The sensitivity results are given for the -290mV half-cell in Figure A-17. These showed that the uncertainty in the corrosion rate had no influence on reliability in a low corrosion situation. The results were sensitive to the same uncertainties as for the as-built case.

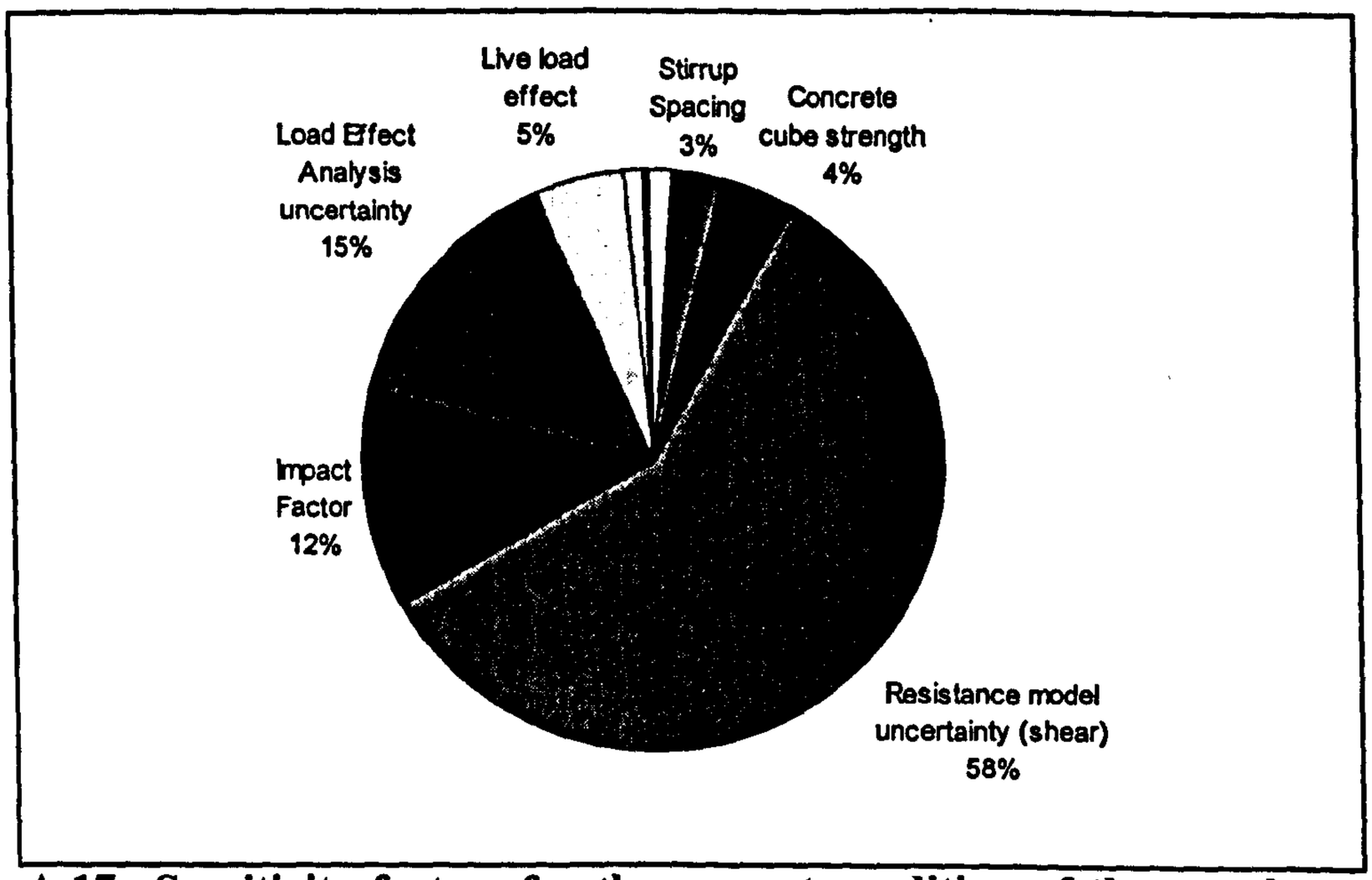


Figure A-17: Sensitivity factors for the present condition of the crossbeam (Low corrosion) - SHEAR LIMIT STATE

APPENDIX 10 Future condition

The crossbeam reliability at different future times was calculated for the shear limit-state basing the reinforcement corrosion on the deterioration model given in Chapter 6, assuming corrosion initiated in 1986. The sensitivity factors for a "high" corrosion rate

over 10 years, presented in Figure A-18, showed the same trend as the present condition. The corrosion coefficient for shear steel dominated for high corrosion rates and was insignificant for low corrosion rates. The results of the mean and standard deviation elasticities have not been shown, but they were also similar to the present condition.

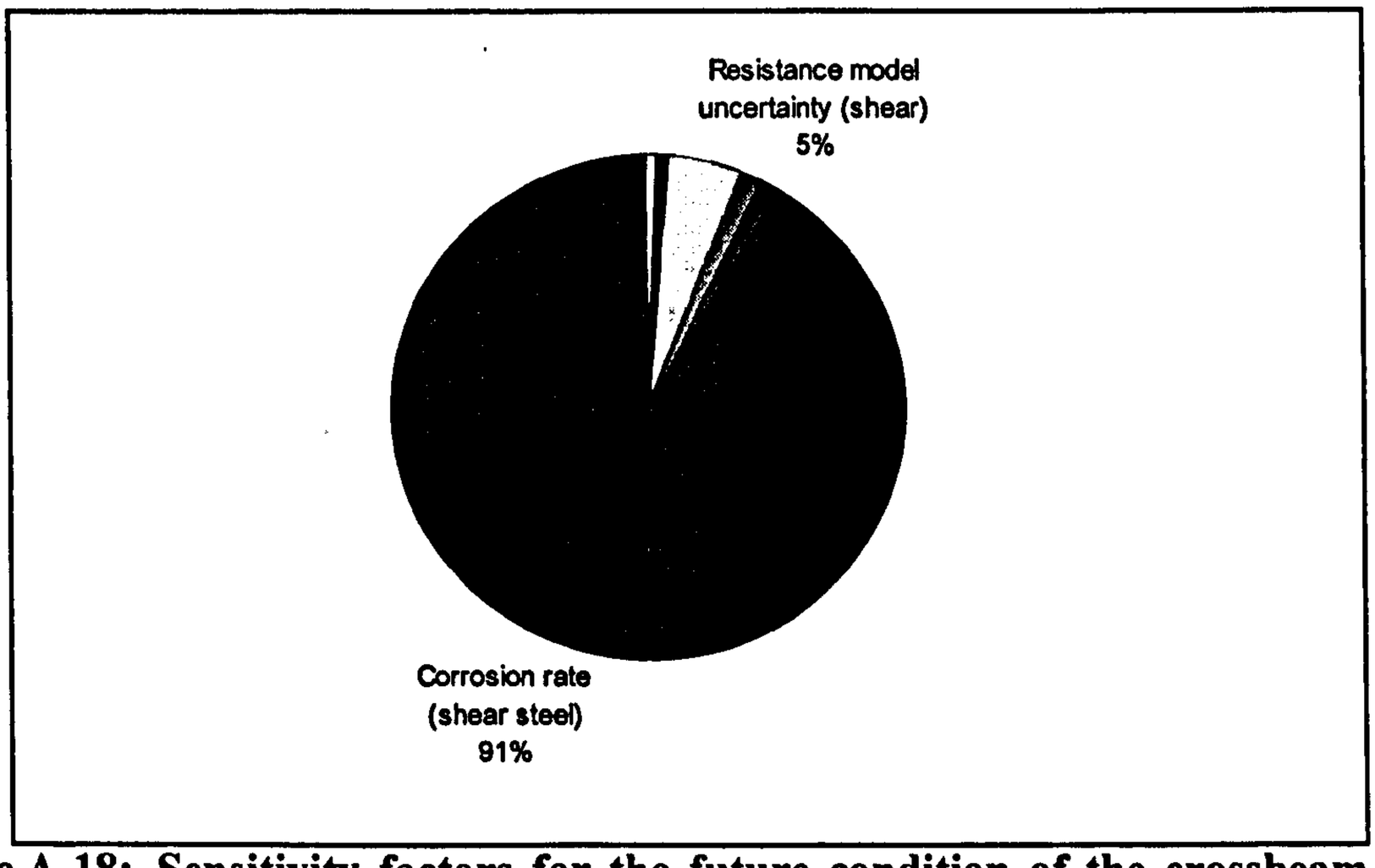


Figure A-18: Sensitivity factors for the future condition of the crossbeam (High corrosion) - SHEAR LIMIT STATE

The results of parametric studies carried out for "low", "medium" and "high" corrosion rates, to study the variation in reliability over time are presented in Figure A-19. The decrease in reliability with time was of the same order as the flexure case. The decrease in reliability was more pronounced for the "medium" and "high" corrosion rate cases.

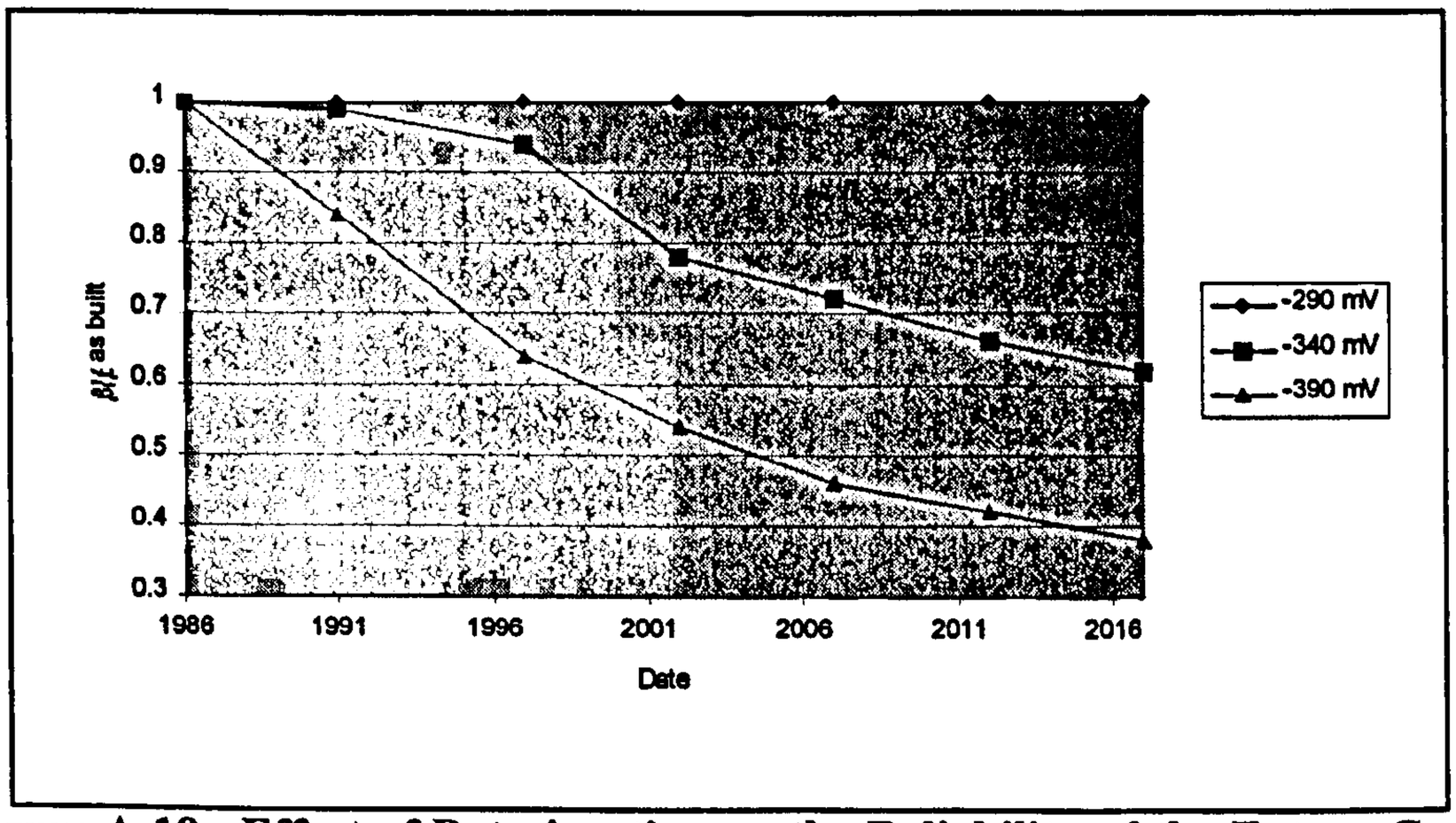


Figure A-19: Effect of Deterioration on the Reliability of the Future Condition of the Crossbeam - SHEAR LIMIT STATE

A10.1 Bond Limit State

APPENDIX 11 As-built condition

The sensitivity results for the as-built condition, in Figure A-20, revealed similar results to the flexure limit state. This is due to the reinforcement developing full tensile capacity hence causing a flexure failure mode.

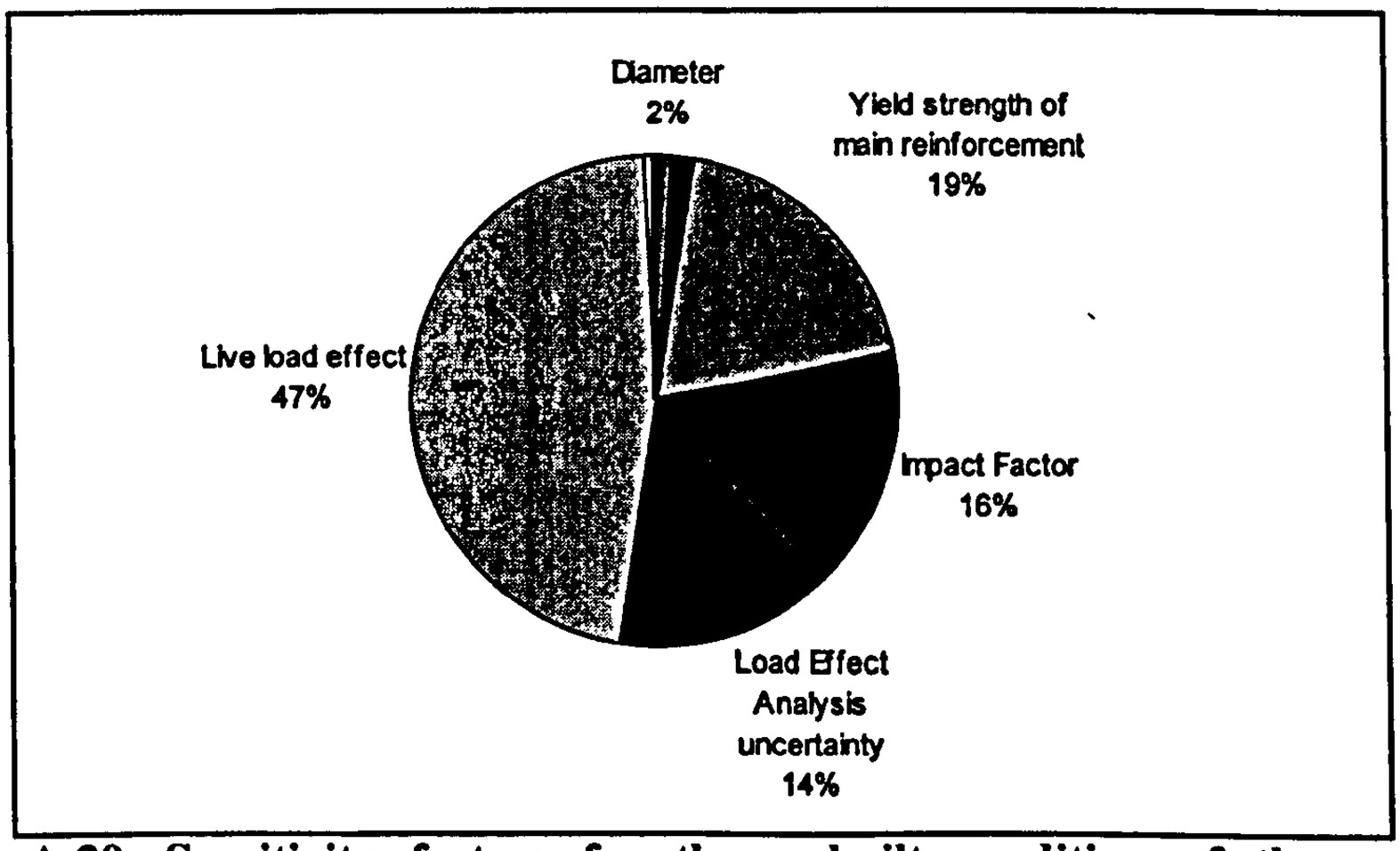


Figure A-20: Sensitivity factors for the as-built condition of the crossbeam BOND LIMIT STATE

The elasticities of the variable mean values, presented in Figure A-21, were high for the main reinforcement yield strength, the load effect analysis model and the bar diameter s.

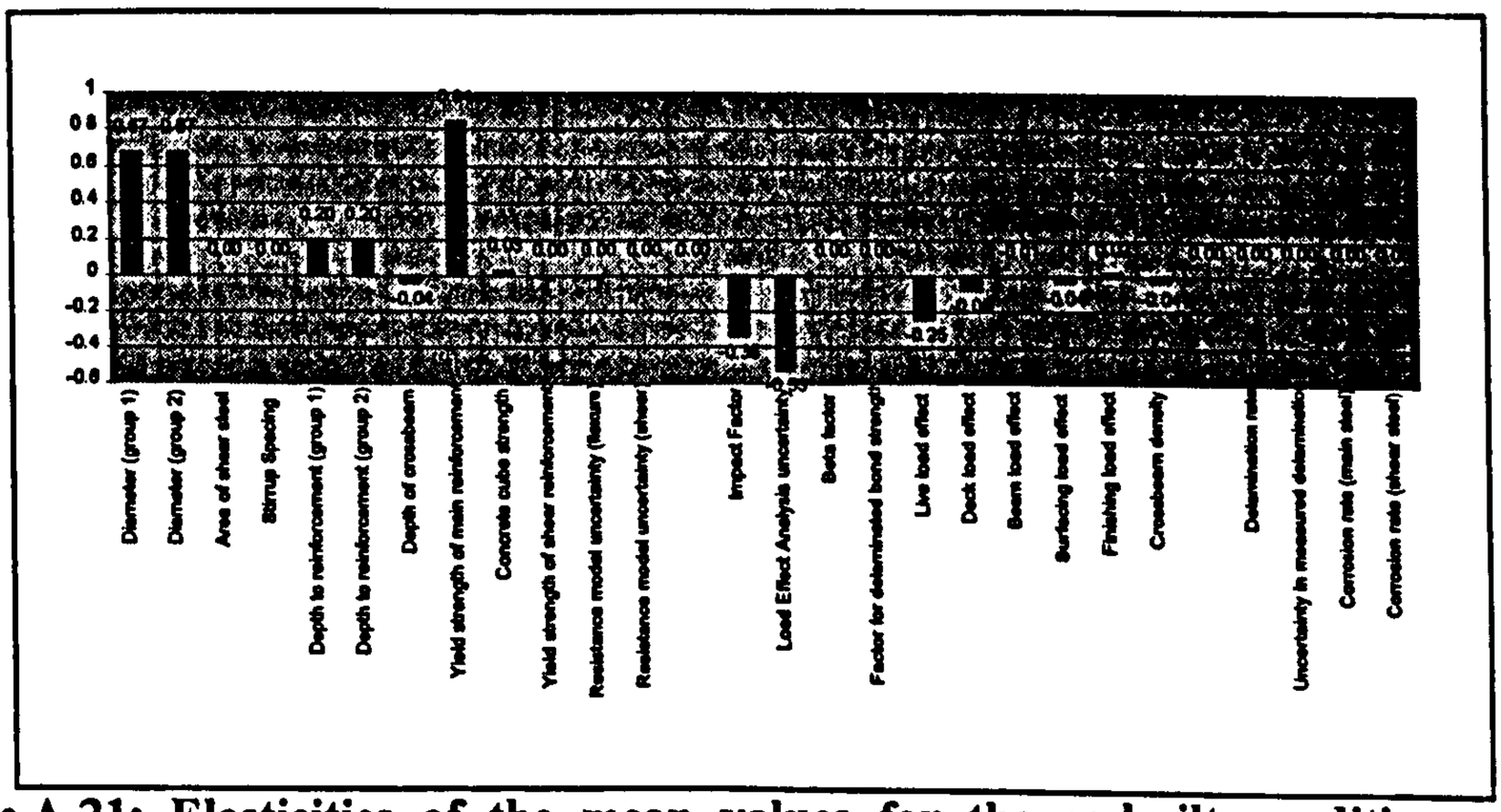


Figure A-21: Elasticities of the mean values for the as-built condition of the crossbeam - BOND LIMIT STATE

The elasticities of the standard deviations are shown in Figure A-22. These show that the standard deviations of live load bending moment, impact factor, yield strength of reinforcement and model uncertainty parameters were found to dominate reliability.

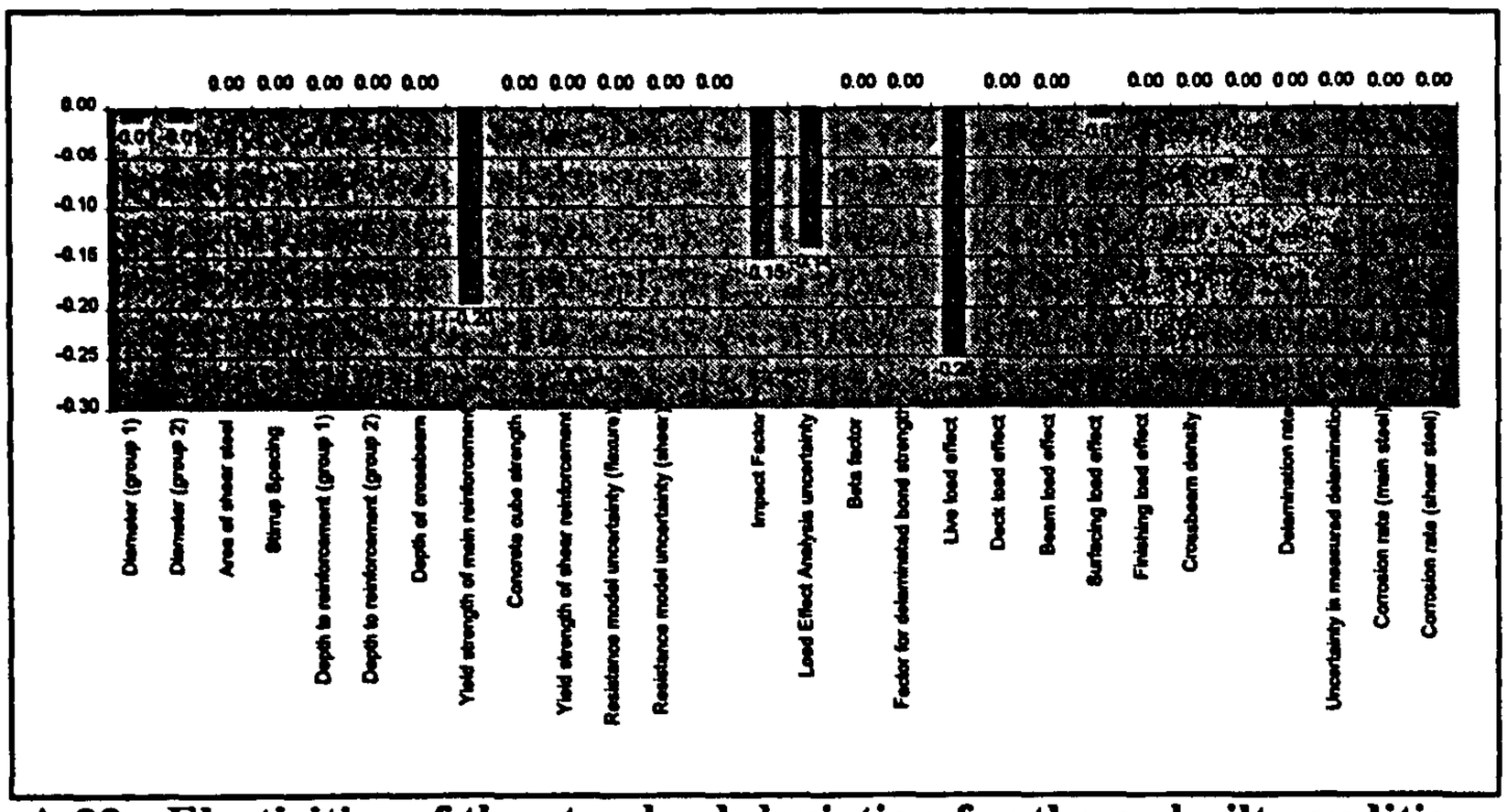


Figure A-22: Elasticities of the standard deviation for the as-built condition of the crossbeam - BOND LIMIT STATE

APPENDIX 12 Present condition

For the present condition, the corrosion of longitudinal and shear reinforcement over time was calculated using the deterioration model in Chapter 6, assuming that corrosion initiated in 1986. About 30% of the anchorage zone of the crossbeam was assumed to be delaminated. The loss of concrete in the compressive zone was not included.

The sensitivity results for the "high" corrosion rate case, in Figure A-23, showed that the crossbeam reliability was dominated by the corrosion rate uncertainty. Because of a high loss of reinforcement area, the tensile capacity was lower than the bond capacity (i.e. resistance to slip), hence a flexure failure mode.

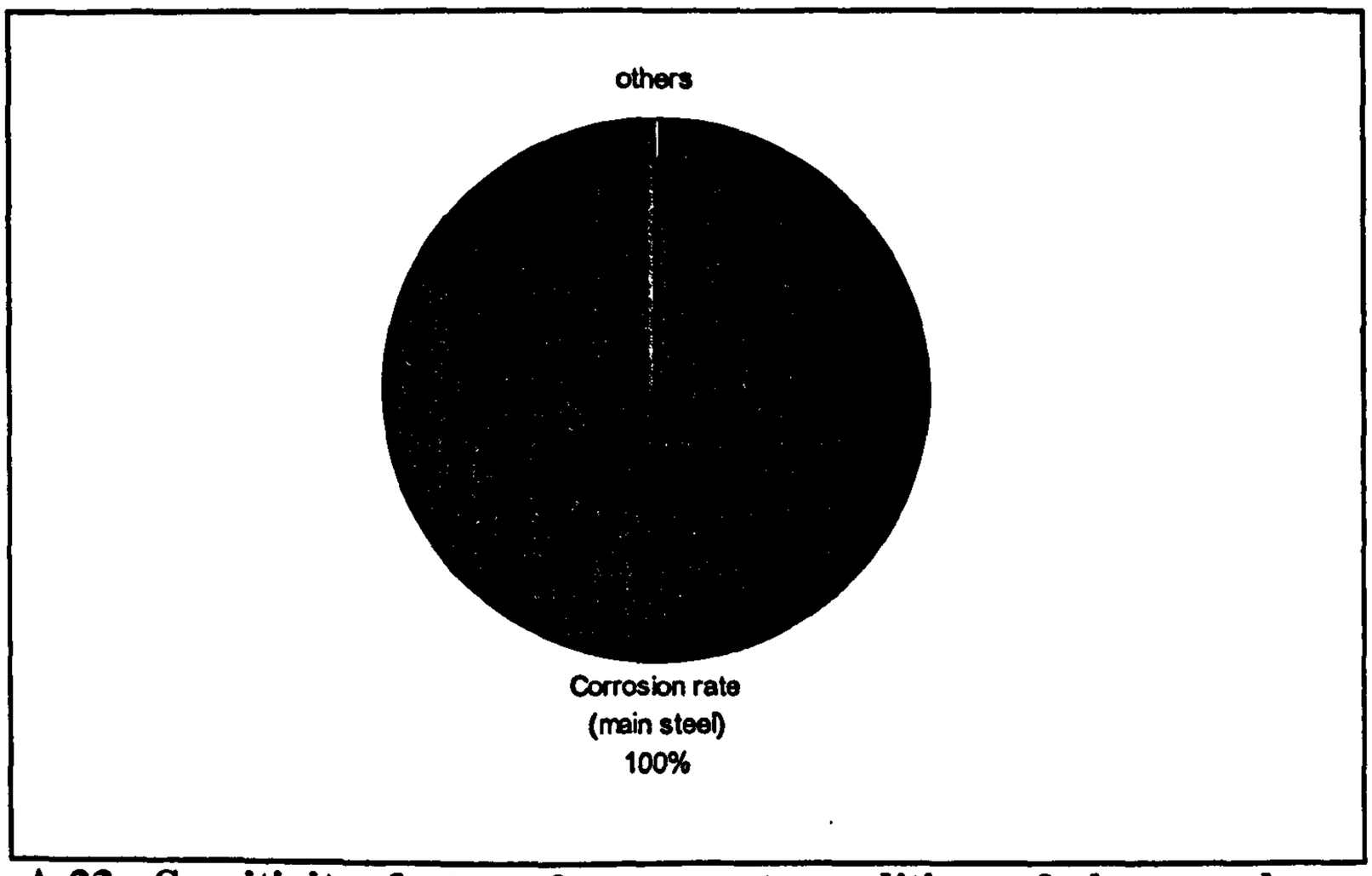


Figure A-23: Sensitivity factors for present condition of the crossbeam (high corrosion) - BOND LIMIT STATE

The elasticities of the variable mean values and standard deviations, in Figure A-24 and Figure A-25 were also similar to those of the flexure case in the present condition.

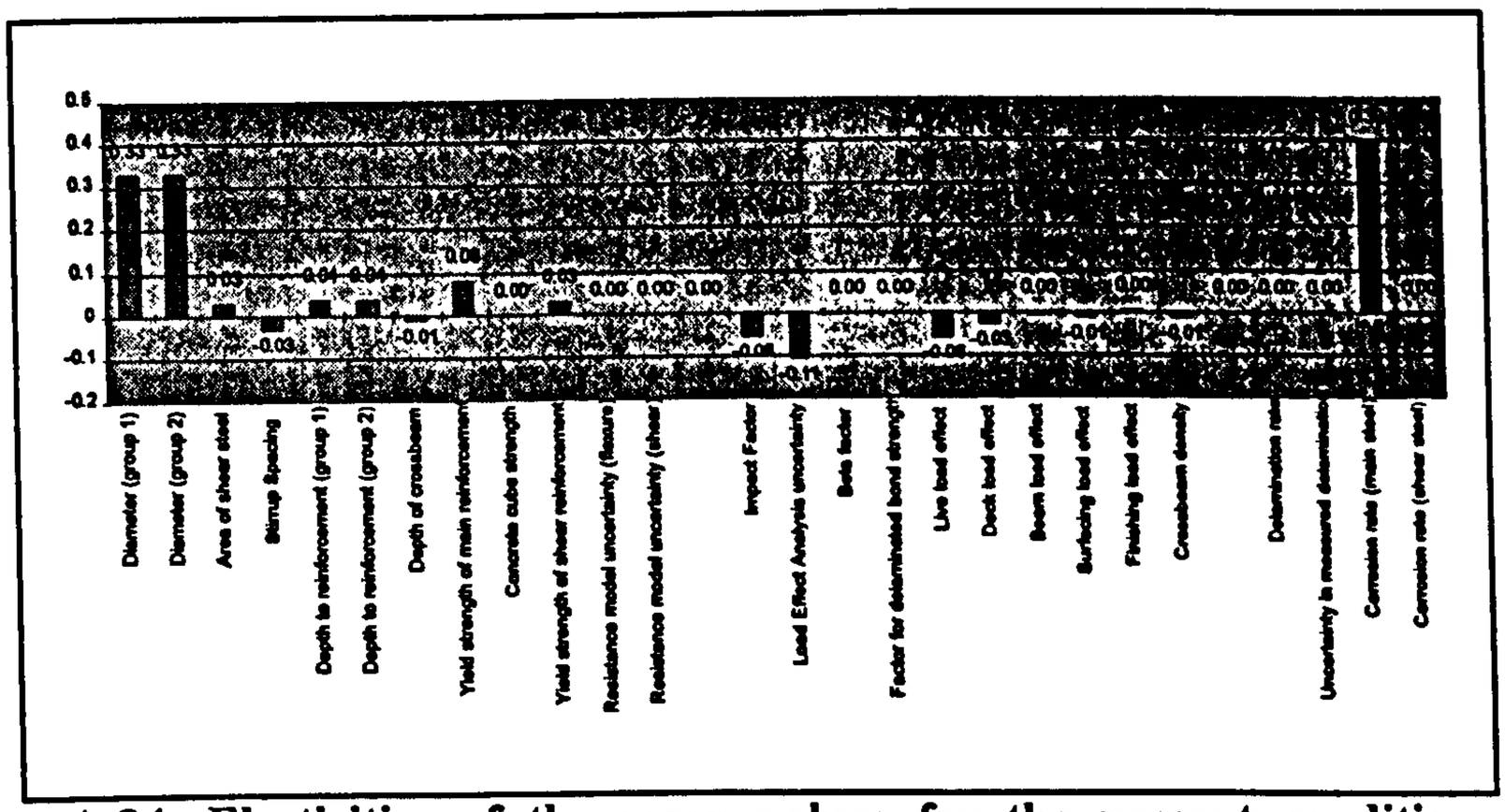


Figure A-24: Elasticities of the mean values for the present condition of the crossbeam (high corrosion rate) - BOND LIMIT STATE

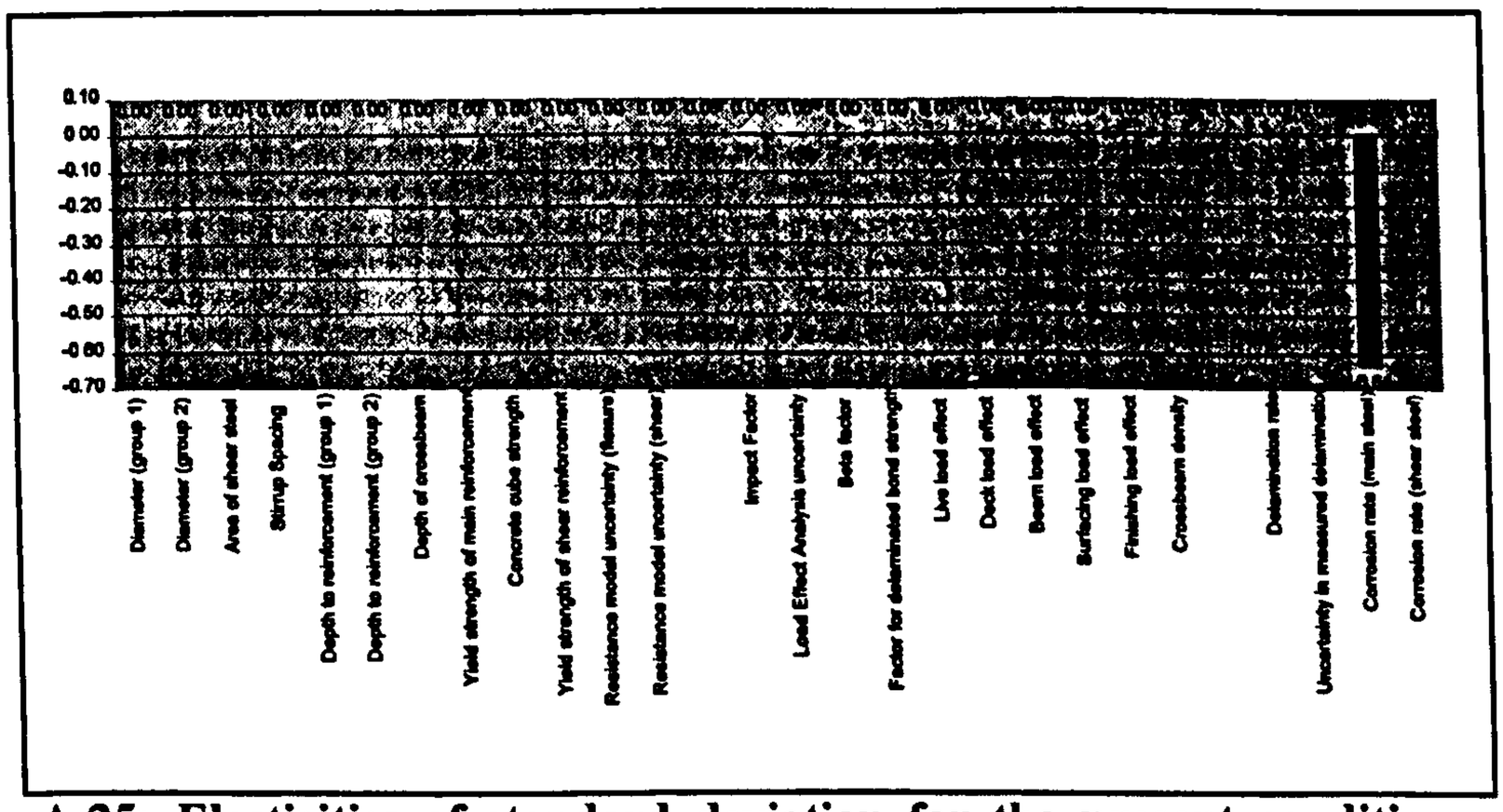


Figure A-25: Elasticities of standard deviation for the present condition of the crossbeam (high corrosion rate) - BOND LIMIT STATE

The sensitivity results for the low corrosion rate (-290mV half cell) case with initial delamination over 30% of the anchorage, in Figure A-26 showed similar important variables to those for bending failure. However, the concrete strength and bond coefficient, β also show a significant influence on the reliability. The design point values showed that if the anchorage zone was moderately delaminated, it was likely to result in a combination of bond and bending failure. The bars with the shortest minimum anchorage length (for the considered section) were likely to fail by bond (slipping) but the bars with the longer minimum anchorage length were able to mobilise enough bond strength to resist slipping. The section failed by yielding the longer bars.

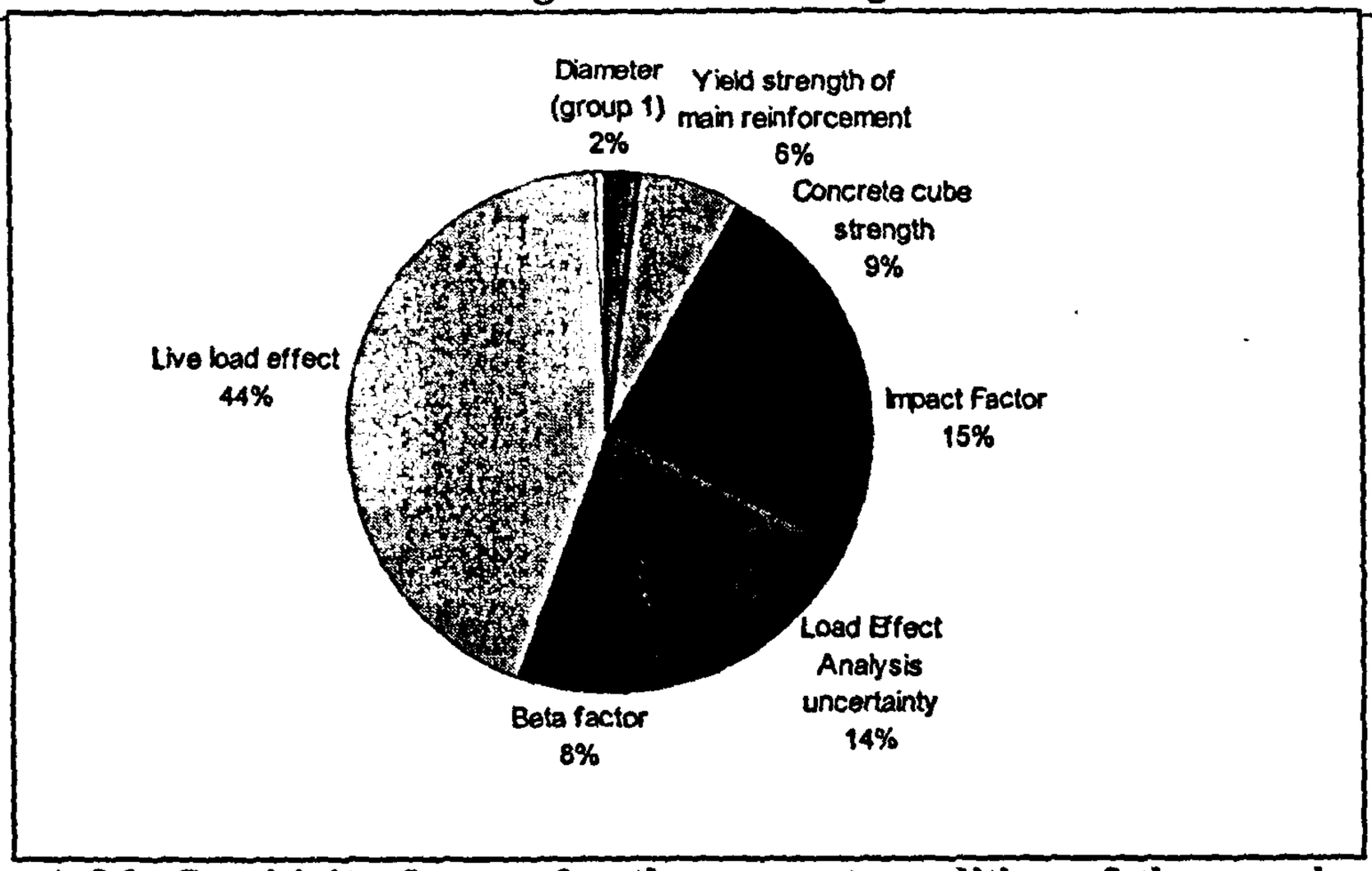


Figure A-26: Sensitivity factors for the present condition of the crossbeam (low corrosion rate) - BOND LIMIT STATE

To study the effect of high delamination, a fully delaminated anchorage zone was considered. The sensitivity results in Figure A-27 show that the factor η on delaminated bond strength, the bond coefficient β and the concrete cube strength dominate. The delaminated bar capacity was limited by bond strength hence slipping failure.

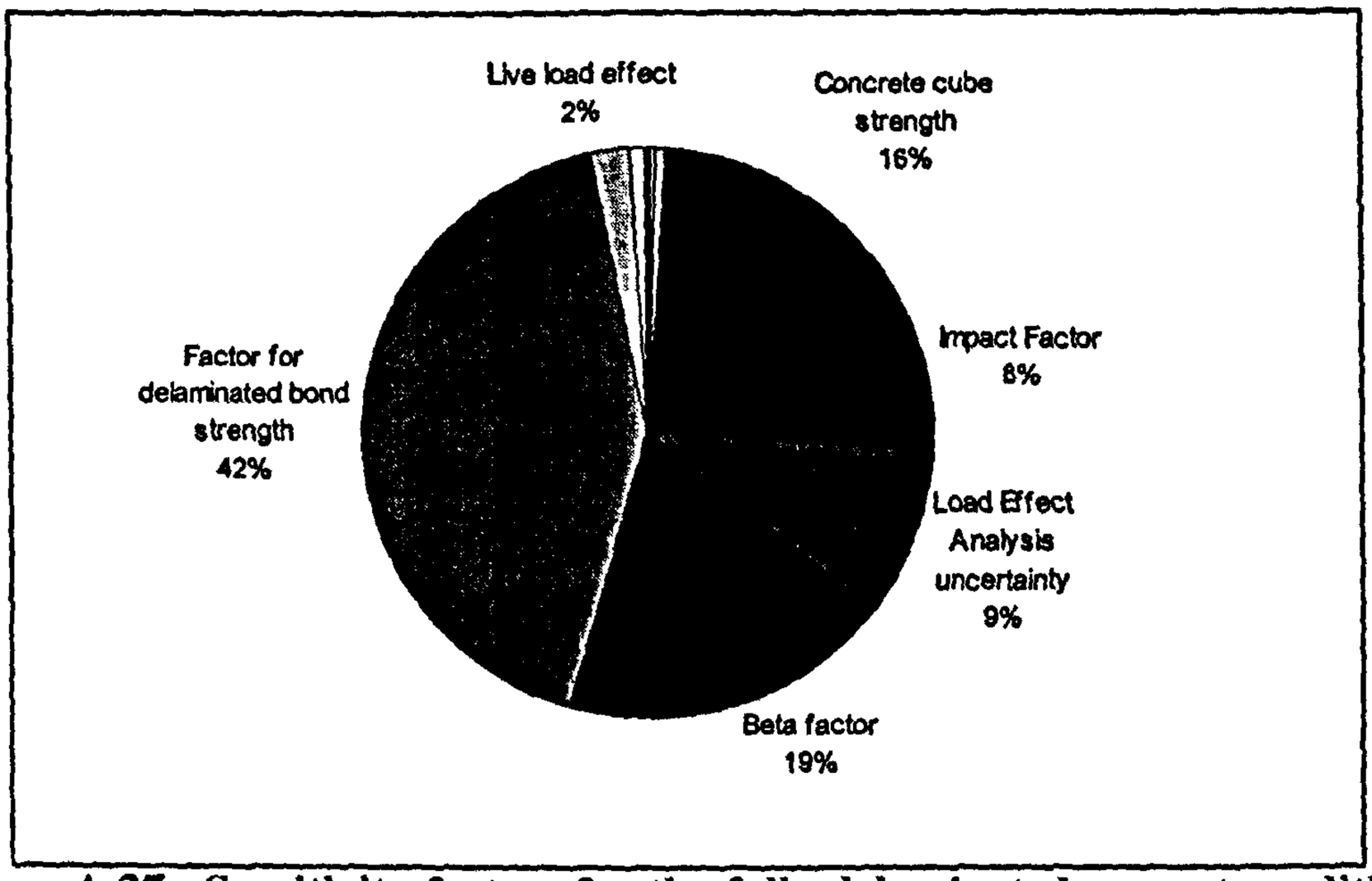


Figure A-27: Sensitivity factors for the fully delaminated present condition of the crossbeam (low corrosion rate) - BOND LIMIT STATE

When the initial delamination area was small, reinforcement bars mobilised full tensile capacity causing flexure failure. When the area of delamination increases gradually, the failure mode changes over to a bond type. The point at which this change over happened depended on the section considered, the length of the bars and the force in the bars. The loss of shear links (not considered here) could have initiated an early change over, while the clamping of bars would have delayed it. For high corrosion rates, flexure failure was more likely with the reliability dominated by corrosion rate uncertainty.

APPENDIX 13 Future condition

The crossbeam reliability at different future times was studied for the bond limit-state. The sensitivities changed depending on the governing failure mode. For high corrosion rates (over 10 years), the failure mode was flexure, hence the reliability was governed by the corrosion rate uncertainty (Figure A-28). However, for "low" corrosion rates, the delamination rate uncertainty dominated (Figure A-29). Uncertainties in β coefficient and η factor on delaminated bond strength also became significant. The results of mean and the standard deviation elasticities were in general similar to the present condition.

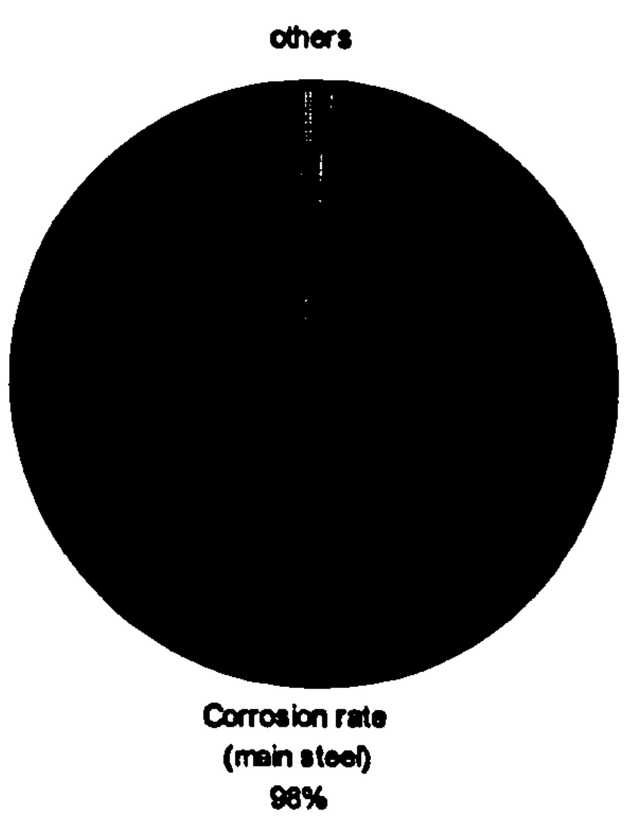


Figure A-28: Sensitivity factors for the future condition of the crossbeam (high corrosion rate) - BOND LIMIT STATE

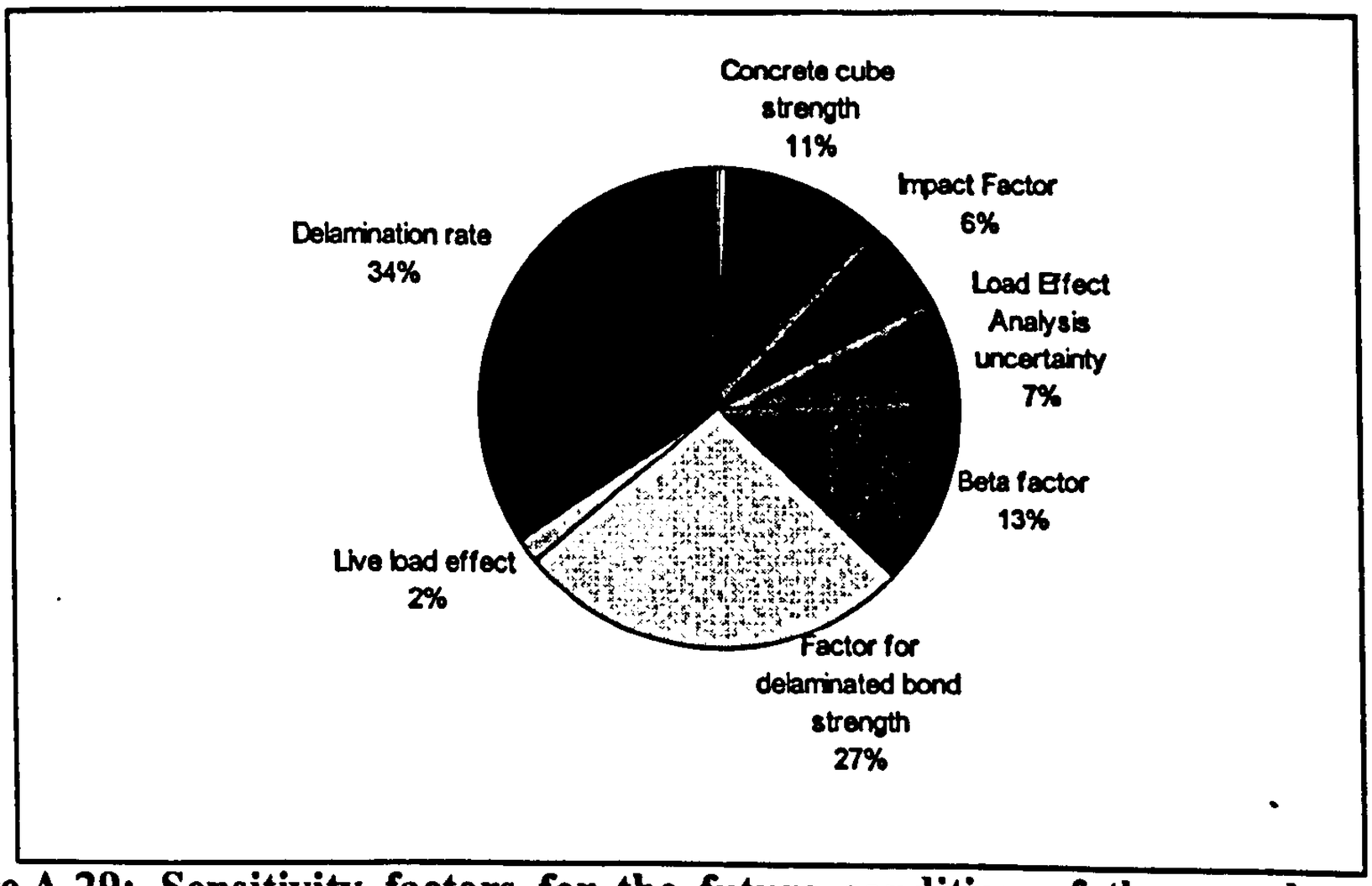


Figure A-29: Sensitivity factors for the future condition of the crossbeam (low corrosion rate) - BOND LIMIT STATE

Parametric reliability analyses carried out for "low", "medium" and "high" corrosion rates to study the variation in reliability over time are shown in Figure A-30. For

"medium" and "high" corrosion rates, the reliability dropped dramatically with time. For the "low" corrosion rate, the reliability was initially unaffected, then dropped suddenly once a critical delamination level was reached, the reliability level then re-stabilised. The sensitivities showed flexure type failure for the "moderate" and "high" corrosion rate cases, giving a similar variation of reliability with time to the flexure limit state.

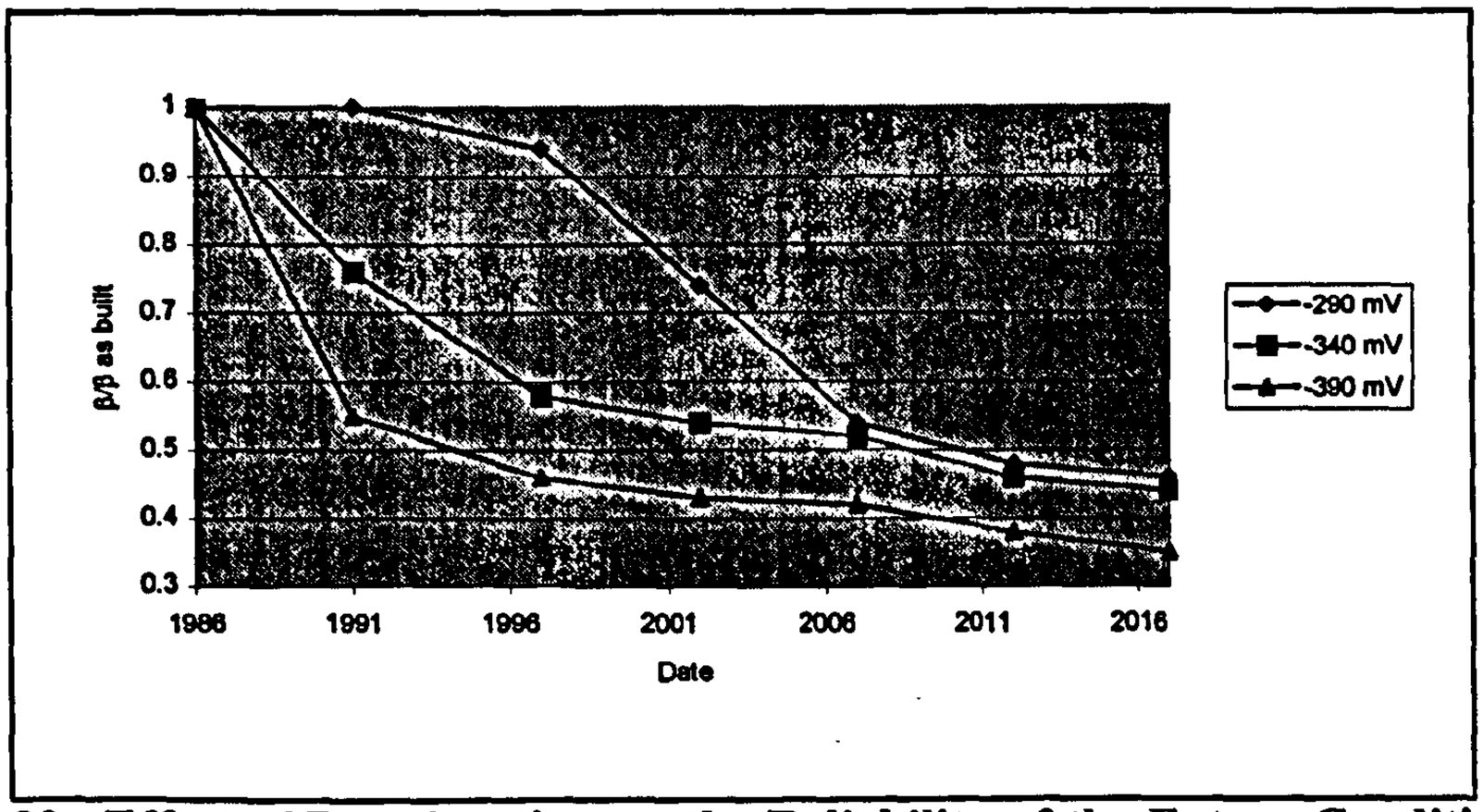


Figure A-30: Effect of Deterioration on the Reliability of the Future Condition of the Crossbeam - BOND LIMIT STATE

For a "low" corrosion rate, the sensitivities change as the failure mode changes from flexure to bond (Figure A-31). Before 1997 the delamination was small, implying flexure failure, hence yield strength and impact factor dominated. After this, the delamination rate uncertainty became important until a critical delamination level was reached. As the delamination stabilised, the reliability was governed by the uncertainty in β coefficient and η factor on delaminated bond strength.

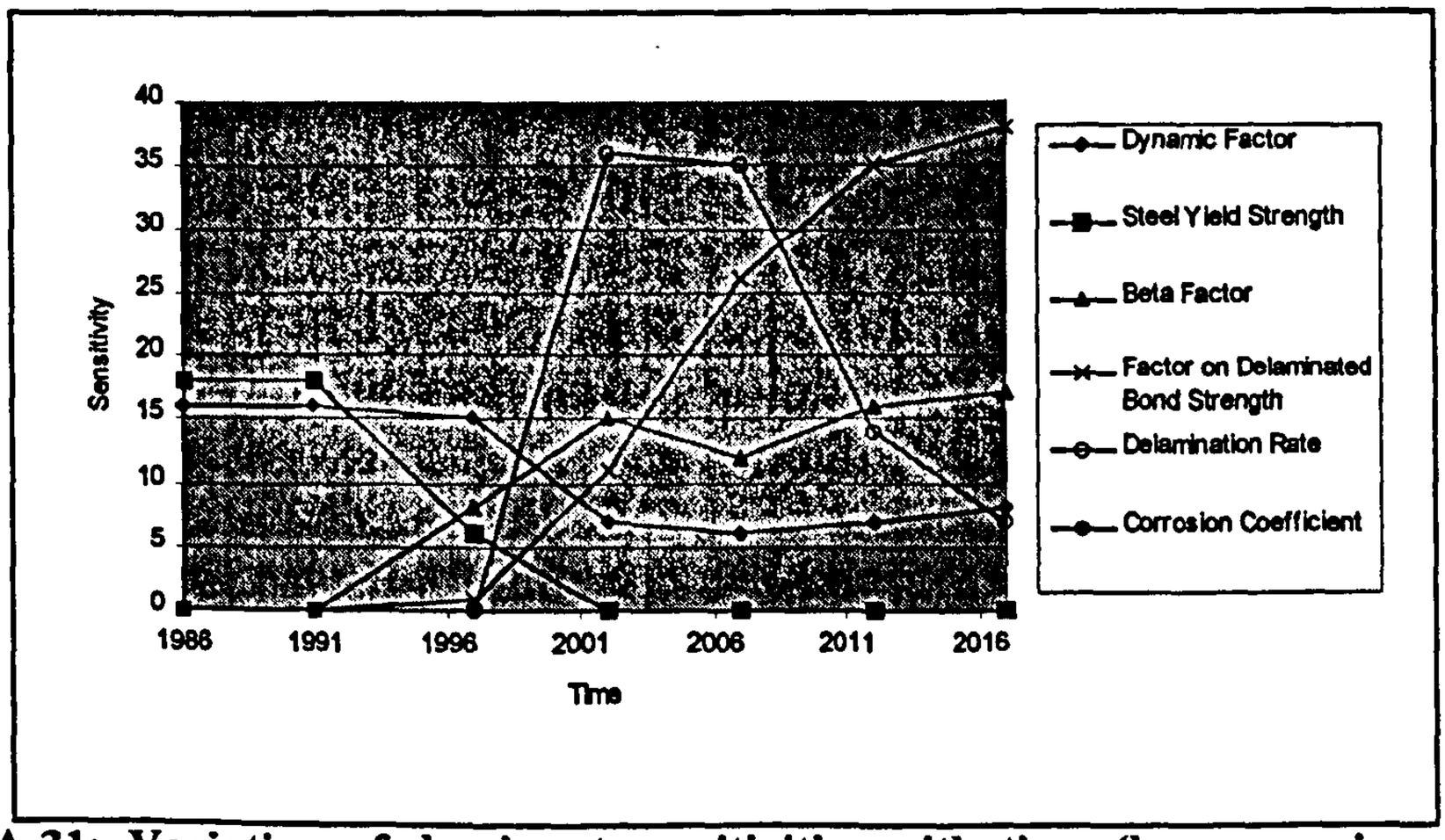


Figure A-31: Variation of dominant sensitivities with time (low corrosion rate) BOND LIMIT STATE

APPENDIX 5 INTERVIEW RESPONSE SHEET FOR DERIVING CRITERION WEIGHTS IN CASE STUDY 4

A5.1 Introduction

This questionnaire uses the Analytic Hierarchy Process (AHP) [3] to compare between the important criteria so that relative weights can be determined. This ultimately allows a "Bridge Priority Index" (BPI) to be calculated for each bridge, by aggregating each bridge's scores for each main criterion to define the relative weights with this questionnaire's results.

A5.2 The Main Criteria for Prioritisation

A5.2.1 Defining the Main Criteria

The bridge prioritisation decision is to be based on the main criteria defined below:

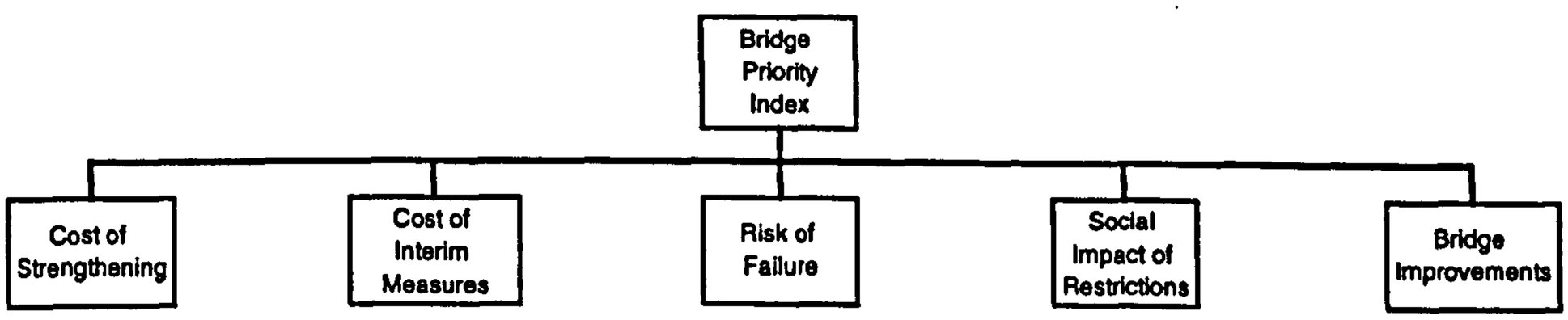


Figure A-32: Proposed main criteria for deriving bridge strengthening priorities

A5.2.1.1 Cost of Strengthening Works

The factors that have been identified to evaluate the cost of strengthening works are the cost of works, the cost of traffic management measures, and the cost of traffic delays during the works.

A5.2.1.2 Cost of Interim Measures

The cost of interim measures would include the costs associated with implementing, weight restrictions, lane restrictions, propping, traffic delays and diversions.

A5.2.1.3 Risk of Bridge Failure

The risk would be evaluated as a function of the probability of failure and its consequences. The consequences of failure include the costs of emergency repairs, the cost of traffic disruption caused by the closure of the bridge, costs associated with fatalities, injuries, and environmental damage that may occur due to bridge collapse.

A5.2.1.4 Social Impact of Restrictions

This covers all of the non-costed impacts on the local community of the traffic restrictions on the bridge such as, the inconvenience of bus routes being diverted away from their usual stops and the discomfort of HGVs being diverted through residential areas, etc. These impacts would depend on the type of traffic and the daily traffic flow on the route, the type of route and the availability of alternative routes.

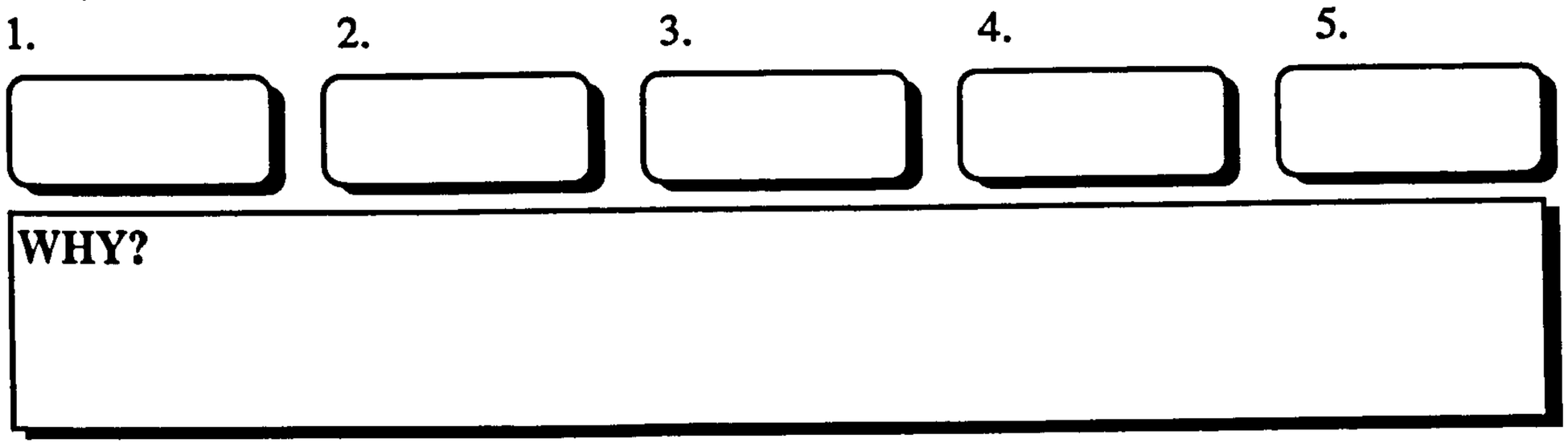
A5.2.1.5 Bridge Improvement Benefits

The types of works considered are strengthening for HB vehicles, carriageway and footway widening, provision of additional services, improving sight distance and strengthening parapets.

A5.2.2 Ordering the main Criteria

The first task, then is to decide the order of preference for these five criteria starting with the most important.

- Cost of Strengthening
- Social Impact of Restrictions
- Risk of Failure
- Bridge Improvement Benefits
- Cost of Interim Measures



A5.3 The Sub-Criteria for Calculating the Main Criteria

Within two of the main criteria are sub-criteria that need to be ordered and weighted to allow scores for these two main criteria to be calculated. These criteria are 1) impact on society due to restrictions and 2) bridge improvement benefits.

A5.3.1 Social Impact of Restrictions

A5.3.1.1 Defining the Sub-Criteria

The sub-criteria on which the impact on society is to be based are divided into two groups: the category of the route and the importance of the route. The category of the route will be evaluated from the daily traffic flow on the route and the type of route (i.e. Primary Route, Borough Principal Route, etc.). The importance of the route will be based on the type and numbers of vehicles using the route and the availability of alternative routes for each type of vehicle.

A5.3.1.2 Ordering the Sub-Criteria

Route Category vs. Route Importance

Firstly, the order of preference for the two main groups has to be determined. Which should carry more weight in your opinion, the type of route (and total number of vehicles using it daily), or the importance of the route to different types of special users?

1. 2.

WHY?

Ordering the criteria for Route Category

Within the criteria for route category, it is necessary to decide the order of preference for the following route types starting with the most important.

- Local distributor route
- Borough principal route
- Primary route
- Local access route

1. 2. 3. 4.

WHY?

Ordering the criteria for Route Importance

Within the criteria for route importance, it is necessary to decide the order of preference for the different users according to the availability of alternative routes.

- Cyclists
- Buses
- Fire engines
- Pedestrians
- HGVs
- Other emergency vehicles

1. 2. 3. 4. 5. 6.

WHY?

A5.3.2 Bridge Improvement Benefits

A5.3.2.1 Define the Sub-Criteria

The benefits of bridge improvement works depend on the types of bridge improvement works that are carried out. The types of works being considered are strengthening for HB vehicles, carriageway widening, footway widening, provision of additional services, improvement of sight distance and strengthening of the parapets. If a certain type of improvement work is proposed it will score a one, if not, it will score a zero.

A5.3.2.2 Order the Sub-Criteria

Some bridge improvement works will be more beneficial than others, so this order of preference has to be determined, starting with the most important.

- Footway widening
- Strengthening for HB vehicles
- Provision of additional services
- Improvement of sight distance
- Strengthening of the parapets
- Carriageway widening

1.	2.	3.	4.	5.	6.

WHY?

A5.4 Evaluate Sub-Criteria Relative Weights

Bridge managers are interviewed to determine the relative importance they attach to criteria pairs. The AHP method calculates the relative weights from these comparisons.

For each pair of criteria, the bridge manager is presented with a pair of example bridges. Each pair of bridges will be almost identical except for the two criteria that are being considered. For each pair of criteria the bridge manager will be asked to select which bridge would be funded.

Within two of the main criteria are the groups of sub-criteria that need to be weighted to allow scores for these two main criteria to be calculated.

A5.4.1 Evaluate Sub-Criteria Relative Weights: Bridge Improvement Benefits

The score for bridge improvement benefits is based on all of the upgrading works proposed to be carried out along with the bridge strengthening works. The assessing engineer just states yes/no to include each upgrading type. All proposed works score 1 and all that are not proposed score 0.

To calculate the weightings for the different improvements, each type of improvement will have to be compared. The decision maker is asked to state which is considered more important. If there is no preference for one over the other, the two improvements will be considered to be equally important. If, however, there is a preference between them, then the decision maker is asked to indicate the 'strength' of their preference on the following scale:

1	Equally preferred
3	Weak preference
5	Strong preference
7	Very strong preference
9	Absolute preference

Pair comparisons (a)	(b)	Dominant improvement type (a or b)	Strength of Dominance (from weighting table)
Strengthen for HB or Additional services	Sight distance or Footway width		
Carriageway width or Strengthen Parapet	Strengthen for HB or Additional services		
Sight distance or Footway width	Carriageway width or Strengthen Parapet		

A5.4.2 Evaluate Sub-Criteria Relative Weights: Social Impact of Restrictions

The sub-criteria for impact on society are divided into: route category and route importance. The way in which each of these is to be evaluated will be considered first.

A5.4.2.1 Evaluating Sub-Criteria Relative Weights: Route Category

Primary/Borough Principal Route vs. Local Distributor/Access Route

Case	Bridge 1		Bridge 2	
1	Primary/Borough Principal road, >25000 vpd		Local distributor road, <15000 vpd	
2	Primary/Borough Principal road, 20000-25000 vpd		Local access road, <10000 vpd	
3	Primary/Borough Principal road, 10000-20000 vpd			

A5.4.2.2 Evaluating Sub-Criteria Relative Weights: Route Importance

PSVs vs. HGVs

Case	Bridge 1		Bridge 2	
1	>3000 PSVs /day : <1000 HGVs /day		>3000 HGVs /day : <1000 PSVs /day	
2	2000-3000 PSVs /day : <1000 HGVs /day		2000-3000 HGVs /day : <1000 PSVs /day	
3	1000-2000 PSVs /day :<1000 HGVs /day		1000-2000 HGVs /day : <1000 PSVs /day	
4	<1000 PSVs /day : <1000 HGVs /day		<1000 HGVs /day : <1000 PSVs /day	

Fire Engines/Emg. Vehicles vs. PSVs/HGVs

Case	Bridge 1		Bridge 2	
1	Very important for Fire Engines/Emergency Vehicles <1000 PSVs or HGVs day		Not important for Fire Engines/Emergency Vehicles > 3000 PSVs or HGVs /day	
2	Important for Fire Engines/Emergency Vehicles <1000 PSVs or HGVs /day		Not important for Fire Engines/Emergency Vehicles 2000-3000 PSVs or HGVs /day	
3	Not important for Fire Engines/Emergency Vehicles <1000 PSVs or HGVs / day		Not important for Fire Engines/Emergency Vehicles 1000-2000 PSVs or HGVs /day	
4			Not important for Fire Engines/Emergency Vehicles <1000 PSVs or HGVs per day	

PSVs/HGVs vs. Cyclists/Pedestrians

Case	Bridge 1		Bridge 2	
1	Not important for cyclists or pedestrians >3000 PSVs or HGVs /day		London Cycle Network or very important for pedestrians <1000 PSVs or HGVs /day	
2	Not important for cyclists or pedestrians 2000-3000 PSVs or HGVs /day		Important for cyclists or pedestrians <1000 PSVs or HGVs /day	
3	Not important for cyclists or pedestrians 1000-2000 PSVs or HGVs /day		Not important for cyclists or pedestrians <1000 PSVs or HGVs /day	
4	Not important for cyclists or pedestrians <1000 PSVs or HGVs /day			

Fire Engines/Emg. Vehicles vs. PSVs/HGVs

Case	Bridge 1		Bridge 2	
1	Very important for Fire Engines/Emergency Vehicles Not important for cyclists/pedestrians		London Cycle Network / important for pedestrians Not important for Fire Engines/Emergency Vehicles	
2	Important for Fire Engines/Emergency Vehicles Not important for cyclists/pedestrians		Important for cyclists or pedestrians Not important for Fire Engines/Emergency Vehicles	
3	Not important for Fire Engines/Emergency Vehicles Not important for cyclists/pedestrians		Not important for cyclists or pedestrians Not important for Fire Engines/Emergency Vehicles	

A5.4.2.3 Route Category vs. Route Importance

The sub-criteria for impact on society are divided into: route category and importance:

Case	Bridge 1		Bridge 2	
1	Route Category is v. high (Primary/Borough Principal road, >25 000 vpd) Route Importance is v. low		Route Importance is v. high (>3000 PSV or HGV, v. important for F.E.s & Emg. Veh) Route Category is v. low	
2	Route Category is high (Primary/ Borough Principal road, 20 000-25 000 vpd) Route Importance is v. low		Route Importance is high (2000-3000 PSV / HGV, v. important for F.E.s & Emg. Veh) Route Category is v. low	
3	Route Category is med (Primary/ Borough Principal road, 10 000-20-000 vpd) Route Importance is v. low		Route Importance is med (1000-2000 PSV or HGV, important for F.E.s & Emg. Veh) Route Category is v. low	
4	Route Category is low (Local Distributor road, less than 15 000 vpd) Route Importance is v. low		Route Importance is low (1000-2000 PSV or HGV, no Fire Engines or Emg. Veh) Route Category is v. low	
5	Route Category is v. low (Local Access road, less than 10 000 vpd) Route Importance is v. low		Route Importance is v. low (<1000 PSV/ HGV, no Fire Engines/Emg. Vehicles) Route Category is v. low	

A5.5 Evaluating the Relative Weights of the Main Criteria

A5.5.1 Risk of failure vs. Cost of interim measures

Case	Bridge 1		Bridge 2	
1	Risk of failure is v. high (Cap. Ratio=0.6; Failure prob.=1 in 100; Fatalities=15; Traffic delay cost >£300m) Interim measure cost is v. low		Interim measure cost is v. high (daily = £2m; annual cost = £750m) Risk of failure is v. low	
2	Risk of failure is high (Cap. Ratio=0.7; Failure prob.==1 in 103; Fatalities=5; Traffic delay cost =£100m) Cost of interim measures is v. low		Interim measure cost is high (daily = £1m; annual cost = £350m) Risk of failure is v. low	
3	Risk of failure is med(Cap. Ratio =0.8; Failure prob.==1 in 104; Fatalities=1; Traffic delay cost =£50m) Cost of interim measures is v. low		Interim measure cost is med (cost = £250k; annual cost = £90m) Risk of failure is v. low	
4	Risk of failure is low (Cap. Ratio =0.9; Failure prob.==1 in 105; Fatalities=0; Traffic delay cost =£5m) Cost of interim measures is v. low		Interim measure cost is low (cost = £25k; annual cost = £9m) Risk of failure is v. low	
5	Risk of failure is v. low (Cap. Ratio =0.95; Failure prob.==1 in 106; Fatalities=0; Traffic delay cost =£500k) Cost of interim measures is v. low		Interim measure cost is v. low (cost< £5k; annual cost < £1.8m) Risk of failure is v. low	

A5.5.2 Risk of failure vs. Social impact of restrictions

Case	Bridge 1		Bridge 2	
1	Risk of failure is v. high (Cap. Ratio=0.6; Failure prob.=1 in 100; Fatalities=15; Traffic delay cost >£300m) Social impact of restrictions is v. low		Social impact of restrictions = v. high (Primary/B.P. road, 30k vpd, 4k PSV/HGV, v. imp. F.E. & Emg. Veh) Risk of failure is v. low	
2	Risk of failure is high (Cap. Ratio =0.7; Failure prob.==1 in 103; Fatalities=5; Traffic delay cost =£100m) Social impact of restrictions is v. low		Social impact of restrictions is high (Primary/ B.P. road, 20k vpd, 3k PSV/HGV, v. imp. F.E. & Emg. Veh) Risk of failure is v. low	
3	Risk of failure is med (Cap. Ratio =0.8; Failure prob.==1 in 104; Fatalities=1; Traffic delay cost =£50m) Social impact of restrictions is v. low		Social impact of restrictions is med (Primary/ B.P. road, 15k vpd, 2k PSV/HGV, imp. F.E. & Emg. Veh) Risk of failure is v. low	
4	Risk of failure is low (Cap. Ratio =0.9; Failure prob.==1 in 105; Fatalities=0; Traffic delay cost =£5m) Social impact of restrictions is v. low		Social impact of restrictions is low (Local Distributor road, 12k vpd, 1k PSV/HGV, no F.E. & Emg. Veh) Risk of failure is v. low	
5	Risk of failure is v. low (Cap. Ratio =0.95; Failure prob.==1 in 106; Fatalities=0; Traffic delay cost =£500k) Social impact of restrictions is v. low		Social impact of restrictions is v. low (Local Access road, 5k vpd, 500 PSV/HGV, no F.E. & Emg. Veh) Risk of failure is v. low	

A5.5.3 Cost of Interim measures VS. Social impact of restrictions

Case	Bridge 1		Bridge 2	
1	Cost of interim measures is v. high (daily = £2m; annual cost = £750m) Social impact of restrictions is v. low		Social impact of restrictions = v. high (Primary/ B.P., 30k vpd, 4k PSV/HGV, v. imp. Emg. Veh) Cost of interim measures is v. low	
2	Cost of interim measures is high (daily = £1m; annual cost = £350m) Social impact of restrictions is v. low		Social impact of restrictions is high (Primary/ B.P., 20k vpd, 3k PSV/HGV, v. imp. Emg. Veh) Cost of interim measures is v. low	
3	Cost of interim measures is med (daily = £250k; annual cost = £90m) Social impact of restrictions is v. low		Social impact of restrictions is med (Primary/ B.P., 15k vpd, 2k PSV/HGV, imp. Emg. Veh) Cost of interim measures is v. low	
4	Cost of interim measures is low (daily = £25k; annual cost = £9m) Social impact of restrictions is v. low		Social impact of restrictions is low (Local Dist. road, 10k vpd, 1k PSV/HGV, no Emg. Veh) Cost of interim measures is v. low	
5	Cost of interim measures is v. low (daily < £5k; annual cost < £1.8m) Social impact of restrictions is v. low		Social impact of restrictions is v. low (Local Acc. road, 5k vpd, 500 PSV/HGV, no Emg. Veh) Cost of interim measures is v. low	

A5.5.4 Cost of Interim measures vs. Cost of Strengthening

Case	Bridge 1		Bridge 2	
1	Cost of interim measures is v. high (daily = £2m; annual cost = £750m) Cost of Strengthening is v. high		Cost of Strengthening is v. low (Work cost = £100k, Traffic delay cost = £900k) Cost of interim measures is v. low	
2	Cost of interim measures is high (daily = £1m; annual cost = £350m) Cost of Strengthening is v. high		Cost of Strengthening is low (Work cost = £200k, Traffic delay cost = £4m) Cost of interim measures is v. low	
3	Cost of interim measures is med (cost = £250k; annual cost = £90m) Cost of Strengthening is v. high		Cost of Strengthening is med (Work cost = £500k, Traffic delay cost = £45m) Cost of interim measures is v. low	
4	Cost of interim measures is low (cost = £25k; annual cost = £9m) Cost of Strengthening is v. high		Cost of Strengthening is high (Work cost = £800k, Traffic delay cost = £180m) Cost of interim measures is v. low	
5	Cost of interim measures is v. low (cost< £5k; annual cost < £1.8m) Cost of Strengthening is v. high		Cost of Strengthening is v. high (Work cost = £1m, Traffic delay cost = £380m) Cost of interim measures is v. low	

A5.5.5 Social Impact of Restrictions vs. Cost of Strengthening

Case	Bridge 1		Bridge 2	
1	Social impact of restrictions = v.high (Primary /B.P., 30k vpd, 4k PSV/HGV, v.imp Emg Veh) Cost of Strengthening is v. high		Cost of Strengthening is v. low (Work cost = £100k, Traffic delay cost = £900k) Social impact of restrictions is v. low	
2	Social impact of restrictions is high (Primary/ B.P., 20k vpd, 3k PSV/HGV, v.imp. Emg Veh) Cost of Strengthening is v. high		Cost of Strengthening is low (Work cost = £200k, Traffic delay cost = £4m) Social impact of restrictions is v. low	
3	Social impact of restrictions is med (Primary/ B.P., 15k vpd, 2k PSV/HGV, imp. Emg. Veh) Cost of Strengthening is v. high		Cost of Strengthening is med (Work cost = £500k, Traffic delay cost = £45m) Social impact of restrictions is v. low	
4	Social impact of restrictions is low (Local Dist road, 10k vpd, 1k PSV/HGV, no Emg. Veh) Cost of Strengthening is v. high		Cost of Strengthening is high (Work cost = £800k Traffic delay cost = £180m) Social impact of restrictions is v. low	
5	Social impact of restrictions is v.low (Loc. Acc road, 5k vpd, 500 PSV/HGV, no Emg. Veh) Cost of Strengthening is v. low		Cost of Strengthening is v. high (Work cost = £1m, Traffic delay cost = £380m) Social impact of restrictions is v. low	

A5.5.6 Social Impact of Restrictions vs. Bridge Improvement Benefits

Case	Bridge 1		Bridge 2	
1	Social impact of restrictions = v.high(Primary/ B.P., 30k vpd, 4k PSV/HGV, v.imp. Emg Veh) Bridge improvements are low		Bridge improvement benefits are high (Increase sight distance/Footway widening) Social impact of restrictions is v. low	
2	Social impact of restrictions is high (Primary/ B.P., 20k vpd, 3k PSV/HGV, v.imp. Emg Veh) Bridge improvement benefits are low		Bridge improvement benefits are medium (Carriageway widening/Strengthen parapet) Social impact of restrictions is v. low	
3	Social impact of restrictions is med (Primary/ B.P., 15k vpd, 2k PSV/HGV, imp. Emg. Veh) Bridge improvement benefits are low		Bridge improvement benefits are low (Strengthen for HB / Additional services) Social impact of restrictions is v. low	
4	Social impact of restrictions is low (Loc. Dist. road, 10k vpd, 1k PSV/HGV, no Emg. Veh) Bridge improvement benefits are low			
5	Social impact of restrictions is v.low (Loc.Acc. road, 5k vpd, 500 PSV/HGV, no Emg Veh) Bridge improvement benefits are low			

A5.5.7 Cost of Strengthening VS. Bridge Improvement Benefits

Case	Bridge 1		Bridge 2	
1	Cost of Strengthening is v. low (Work cost = £100k, Traffic delay cost = 900k) Bridge improvement benefits are low		Bridge improvement benefits are high (Increase sight distance/Footway widening) Cost of Strengthening is v. high	
2	Cost of Strengthening is low (Work cost = £200k, Traffic delay cost = £4m) Bridge improvement benefits are low		Bridge improvement benefits are medium (Carriageway widening/Strengthen parapet) Cost of Strengthening is v. high	
3	Cost of Strengthening is med (Work cost = £500k, Traffic delay cost = £45m) Bridge improvement benefits are low		Bridge improvement benefits are low (Strengthen for HB / Additional services) Cost of Strengthening is v. high	
4	Cost of Strengthening is high (Work cost = £800k, Traffic delay cost = £180m) Bridge improvement benefits are low			
5	Cost of Strengthening is v. high (Work cost = £1m, Traffic delay cost = £380m) Bridge improvement benefits are low			

A5.6 What Next

The results of this questionnaire will be processed to determine relative weights for each "family" of criteria in the hierarchy of factors affecting the decision between bridge strengthening bridges. A set of relative weights will be determined for each bridge manager interviewed.

When a number of bridge managers from the different London Boroughs have been interviewed, it will be necessary to combine the different sets of weights to produce a consensus set of weights. An algorithm, called the "modified median consensus algorithm" [4] can be used for this purpose. The modified median consensus algorithm also provides a measure of the group cohesiveness, to indicate how closely each of the individuals agree.

If there is wide disagreement (e.g. due to wide variations in policy and culture within each authority), multi-dimensional mapping can be used to identify the key differences. This will establish if there is just one or two individuals with very different views to the rest of the group, or if the whole group is widely spaced. An understanding of the differences can help to solve them, for example by ensuring all of the criteria have been properly understood, by understanding the reasoning of the individuals and by discussing the implications of these differences in a meeting where all parties are present. This will help to achieve a consensus among all parties.

APPENDIX 6 MATHCAD SPREADSHEETS FOR EVALUATION OF WEIGHTINGS IN CASE STUDY 4

Use of Saaty's "Eigen Value" Method to determine relative preference weight from pairwise comparisons, Saaty (1980)

1. Evaluation of the judgement matrix for the top level family of criteria to determine relative weights for the overall bridge priority index

Group 1

$$M_1 := \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{8} & \frac{1}{7} & 9 \\ 5 & 1 & \frac{1}{7} & \frac{1}{6} & 9 \\ 8 & 7 & 1 & 6 & 9 \\ 7 & 6 & \frac{1}{6} & 1 & 9 \\ \frac{1}{9} & \frac{1}{9} & \frac{1}{9} & \frac{1}{9} & 1 \end{bmatrix}$$

Cost of Strengthening
Cost of Interim
Risk of failure
Social Impact
Bridge Improvements

$i := 0..4$

Find the eigen values of matrix M

$u_1 := \text{eigenvals}(M_1)$

$$u_1 = \begin{bmatrix} 6.335 \\ 0.233 + 2.814i \\ 0.233 - 2.814i \\ -0.901 + 0.717i \\ -0.901 - 0.717i \end{bmatrix}$$

Find the eigen vector corresponding to the principle eigen value

$v_1 := \text{eigenvec}(M_1, u_{1_0})$

$$v_1 = \begin{bmatrix} 0.094 \\ 0.18 \\ 0.89 \\ 0.408 \\ 0.033 \end{bmatrix}$$

Cost of Strengthening
Cost of Interim
Risk of failure
Social Impact
Bridge Improvements

Find the normalised principle eigen vector

$$N_1 := v1_0 + v1_1 + v1_2 + v1_3 + v1_4$$

$$N_1 = 1.603$$

$$v_{n1} := \frac{v_1}{N_1}$$

This gives the relative weights for the top level criteria to determine the overall bridge priority index as follows:

$$v_{n1} = \begin{bmatrix} 0.058 \\ 0.112 \\ 0.555 \\ 0.254 \\ 0.02 \end{bmatrix}$$

Cost of Strengthening
Cost of Interim
Risk of failure
Social Impact
Bridge Improvements

A measure of inconsistency, μ can be calcualted to be used as a comparison between different decision making groups

$$\mu_1 := \left| \frac{u1_0 - 5}{1 - 5} \right|$$

$$\mu_1 = 0.334$$

2. Evaluation of the judgement matrix for the first family of criteria to determine relative weights for the social impact of restrictions

$$M_2 := \begin{pmatrix} 1 & \frac{1}{6} \\ 6 & 1 \end{pmatrix}$$

Route Importance

Route Category

$i := 0..2$

Find the eigen values of matrix M

$u_2 := \text{eigenvals}(M_2)$

$$u_2 = \begin{pmatrix} 2 \\ 0 \end{pmatrix}$$

Find the eigen vector corresponding to the principle eigen value

$v_2 := \text{eigenvec}(M_2, u_{2_0})$

$$v_2 = \begin{pmatrix} 0.164 \\ 0.986 \end{pmatrix}$$

Route Importance

Route Category

Find the normalised principle eigen vector

$N_2 := v_{2_0} + v_{2_1}$

$N_2 = 1.151$

$v_{n2} := \frac{v_2}{N_2}$

This gives the relative weights for the top level criteria to determine the overall bridge priority index as follows:

$$v_{n2} = \begin{pmatrix} 0.143 \\ 0.857 \end{pmatrix}$$

Route Importance

Route Category

A measure of inconsistency, μ can be calcualted to be used as a comparison between different decision making groups

$$\mu_2 := \left| \frac{u_{2_0} - 2}{1 - 2} \right|$$

$\mu_2 = 0$

APPENDIX 7 OUTLINE OF THE INTERVIEW USED IN CASE STUDY 5

A7.1 Interview Approach

A number of recent conceptual and preliminary engineering design projects have been identified and reviewed in detail to establish the types of decisions that APA generally make in a these types of design project [5]. Also identified were the decisions that APA did not make, that were made already by the contractor or the operator. For every key decision, an indication of the main decision makers, the important decision criteria and any constraints on the decision were identified. As a result of this a selection Senior engineers and managers within APA will be identified to be interviewed about the way they make decisions in conceptual and preliminary engineering design projects.

The specific conceptual and preliminary engineering design projects that have been identified will be explored in depth with the project managers and lead engineers that worked on these projects. In addition, project managers and senior engineers will be asked more generally on the usual approach to conceptual and preliminary engineering design decision making and the types of decisions usually encountered. Finally, a number of representatives from contractors and operators will be interviewed on how they see the conceptual design decision making process and to understand how they see us contributing further in the future.

All interviewees will be asked for permission to record the interviews, to ensure that no important information is lost and that the interviewer can concentrate on leading the interview rather than on taking notes.

A7.2 Interview Questions Concerning Specific Project Experience

A number of recent conceptual and preliminary engineering design projects have been identified and reviewed in detail to establish the types of decisions that APA generally make in a design projects. Also identified were the decisions that APA did not make, that were made already by the contractor or the operator. For every key decision, an indication of the main decision makers, the important decision criteria and any constraints on the decision were identified. As a result of this a selection Senior engineers and managers within APA have been identified to be interviewed about the way they made decisions in these conceptual and preliminary engineering design projects. The purpose of the interviews is to try to "paint a picture" of how and why each major decision was made and the issues and risks that were accounted for in it.

The following questions will be asked:

A7.2.1 Identification of the goals

- For the project under consideration, what were the goals ...
- of the design of the end product?

- of each project execution phase?
- Why were these goals considered the most important?
- Who specified these to be the goals?
- How were the goals communicated to others within the project team (and other stakeholders?)
- When in terms of the overall project schedule, were these goals identified and communicated?

A7.2.2Identification of the decisions

- What were the most important decisions?
- Concerning the project management of the design process? (project issues)
- Concerning the actual design of the end product? (design issues)
- Why were they the most important?
- Were these typical or special cases of this type of project?
- Were they handled in a typical manner, or were they handled in a special way?
- If they were handled in a special way describe also the typical way of handling them?
- When were these decisions made?

Considering each of these decisions separately…

- What risks were involved in the decision?
- Were they project risks or design risks?
- How were the risks evaluated?
- What tools/methods were used to assess the risks?
- How was risk defined? (probability, consequence or both?)
- Were risks in financial, safety and environmental terms considered?
- How were they accounted for in the decision?
- Were any risks ignored or considered negligible?
- What was the consequence of ignoring these risks?
- Were any trade-offs specifically made?
- What trade-offs were made?
- Why were trade-offs made?
- How were trade-offs made?
- Who were the Decision makers?
- Whose opinions were accounted for in the decision?
- To what degree were the different parties influential in the decision?
- Were preferences for certain factors or consequences included in the decision, either subjectively or objectively?
- When were the different parties consulted for their opinions?

- With the benefit of hindsight, should anyone else have been consulted who was not included in the decision?
- Who was responsible for the final decision?
- How were the alternatives generated?
- Were any alternatives rejected before being fully evaluated? If so, why?
- What alternative was selected?
- How was the alternative selected?
- Why was the selected alternative chosen?
- What factors /issues were considered to be influential in the way the decision was made?
- How were the important factors identified?
- Were long-term or short term issues dominating?
- Were any factors ignored that should have been considered?
- How were the alternatives measured in terms of the issues?
- What information was gathered to support the decision making?
- When was information gathered to support the decision making?
- Was sufficient information gathered to support the decision making?
- How was it decided whether enough information was gathered?
- What information was not available?
- How was the decision made without it?
- What were the consequences of incomplete information?
- After the decision was made, what evaluation of the decision was made to ensure it was the best decision?

These questions will be asked of the specific project under consideration but also of the way conceptual and preliminary engineering design is carried out in general.

APPENDIX 8 REFERENCES

1 Krishnakumar, K. (1992). **Genetic algorithms: An introduction and an overview of their capabilities.** AIAA guidance, navigation and control conference, Report no. AIAA-92-4462-CP, 728-738.

2 Goldberg, D. E. (1989). Genetic algorithms in search, optimisation and machine learning. Addison Wesley Publishing Co.

3 Saaty, T. L. (1980). The Analytic Hierarchy Process. McGraw-Hill, New York.

4 Royal Military College of Science: Operational Analysis Course Note 285: Formalising Subjective Judgements. Cranfield University, UK.

5 Roberts, C. (1998). Case Study RBD 3: Review of conceptual and preliminary engineering design methods in APA.