TOWARDS ADVANCED BRIDGE MANAGEMENT SYSTEMS

Investigation of the Possibility of Developing an Improved Appraisal Model based on a Novel System Architecture

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"Is what you learn after you know it all
that counts" John Wooden

ABSTRACT

Bridge Management Systems have been an emergent area of research in this decade. This has been fostered by the recognition of the need for computer support in the decision making process involved in defining maintenance and improvement strategies to networks of bridges. While existing systems have already prove their worthiness, there are still far from satisfying entirely the complex and evolving user needs. Changing society perceptions are introducing new requirements and demanding the consideration of issues like environmental quality and congestion minimisation. At the same time, IT developments are opening various new alternatives to the problem of creating flexible, user-friendly and easily maintainable systems.

Given this panorama, this study investigates the possibility of developing more advanced Bridge Management Systems that could lead to a more open, integrated and socially aware approach to Bridge Management. It proposes the adoption of a new appraisal model based on a wider consideration of maintenance and deterioration consequences and an innovative view of bridge utility as a measure of benefits. An innovative system architecture is used to support the model based on three main elements: object orientation, geo-referencing and soft reasoning.

The results obtained indicate that the use of this new approach can significantly alter the allocation of the budget. The conclusion of the work is that it is possible to develop more advanced systems and that the adoption of the framework proposed can have a significant impact on Bridge Management decision-making. Further researches will be necessary to refine the model and investigate how to develop other components of an ABMS. The flexibility of the system architecture proposed is an important advantage in this sense because it allows a progressive and steady advance, with the results of new researches being gradually and seamlessly incorporated.

DEDICATION

To all Brazilian researchers that strive to make the most of the limited resources available in our country, developing a work of love and quality and contributing to improve the standard of life of our people.

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LIST OF ABBREVIATIONS

AASHTO - American Association of State Highway Transportation Officials
ABMS - Advanced Bridge Management Systems
ABNT - Associação Nacional de Normas Técnicas (Brazil)
ADT - Average Daily Traffic
AI - Artificial Intelligence
AV - Asset Value (of a bridge)
AVO - Average Vehicle Occupancy
β - Reliability (of a bridge or element
BF - Belief Strength (of a rule)
BM - Bridge Management
BMS - Bridge Management Systems
BU - Bridge Utility
CA - Conjoint Analysis
CAD - Computer Assisted Design
CBA - Cost Benefit Analysis
CBR - Case-Based Reasoning
CEA - Cost Effectiveness Analysis
CIS - Civil Infrastructure Systems
C_{life} -Cost of a human life
COBA- Cost Benefit Assessment (U.K.)
CR - Cost of Replacement (of a bridge)
CS - Condition State
CUA - Cost Utility Analysis
CVM - Contingency Value Method
D - Disutility
dB - Decibels
dBA - Decibels (instrumentation scale A)
DC - Direct Cost (of a MRI intervention)
DM - Decision-Making
DO - Data-bounded Object
DOT - Department of Transport (U.K.)
DTER - Department of Transport, Environment and the Regions (U.K.)
EC - Environmental Cost
ECI - External Cost of Intervention
ECR - External Cost of Replacement
EI - Environmental Impact
EQ - Environmental Quality
ESR - Element Structural Relevance
FG-BMS - First Generation Bridge Management Systems

FHWA - Federal Highway Administration (U.S.)
FI - Functional Importance (of a bridge)
FINNRA - Finnish Road Authority
FL - Fuzzy Logic
FP -Firing Power (of a fuzzy rule)
FR - Functional Relevance
FV - Functional Value (of a bridge)
GIS - Geographic Information Systems
HA - Highways Agency (U.K.)
HAHT - Homogenised Average Hourly Traffic
HGV - Heavy Goods Vehicles
HI - Historical Importance (of a bridge)
HP - Hedonic Pricing
HR - Historic Relevance
HV - Historic Value (of a bridge)
IBC - Incremental Benefit-Cost ratio
IC - Indirect Cost (of a MRI intervention)
ICE - Institution of Civil Engineers
IS - Information Systems
ISTEA - Intermodal Surface Transportation Efficiency Act
IT - Information Technology
KBS - Knowledge-Based Reasoning
LF - Lifetime (of a bridge)
LGV - Light Goods Vehicles
LOS - Level of Service
MCI - Monetary Cost of Intervention
MDP - Markovian Decision Processes
MF - Membership Function (of a fuzzy number)
MIO - Main Interface Object
MIS - Management Information Systems
MRI - Maintenance, Repair and Improvement
NATS - National Archive for Transportation Structures (U.K.)
NBI - National Bridge Inventory (U.S.)
NBIS - National Bridge Inspection Standards (U.S)
NPV - Net Present Value
NSF - National Science Foundation (U.S.)
OCI - Opportunity Cost of Investment
OECD - Organisation for Economic Co-operation and Development
OGV - Other Goods Vehicles
OMT - Object Modelling Technique
OO - Object Orientation

OOA - Object Oriented Analysis
OOD - Object Oriented Design
OOP - Object Oriented Programming
PMS - Pavement Management Systems
PO - Procedural Object
Psurv - Probability of Survival (of a bridge)
PSV - Passenger Service Vehicle
QUADRO - Queues, Accidents and Delays at Roadworks
RC - Related Cost (of a MRI intervention)
Rf - Risk of Failure
RP - Revealed Preference
SADT - Standard Analysis and Design Technique
SAP - Single Activity Project
SG-BMS - Second Generation Bridge Management Systems
SI - Strategic Importance (of a bridge)
SP - Stated Preference
SS - Structural Soundness (of a bridge)
STR - Strategic Relevance
SUC - Standard Unitary Cost (of a MRI activity)
SV - Strategic Value (of a bridge)
TCM - Travel Cost Method
TG-BMS - Third Generation Bridge Management Systems
Tp - Planning horizon (of a MRI strategy appraisal)
TP - Transition Probabilities
TTC - Time To Change (a Condition State)
UC - User Cost
UCC - User Cost at Collapse
UOC - Unitary Operating Cost (of an equipment)
USDOT - U.S. Department of Transportation
V - Velocity
VBU - Variation in Bridge Utility
VFM - Value For Money
VI - Value Index
VMT - Vehicle-Miles Travelled
VOC - Vehicle Operating Cost
VR - Virtual Reality
VRC - Variation in Replacement Cost
WM - Work Method (used to intervene in a bridge)
WTAC - Willingness to Accept Compensation
WTP -Willingness to Pay

Chapter 1

Introduction

1.1 Definition of the Problem Domain

According to the Institution of Civil Engineers (ICE) in the UK, an efficient and adequate infrastructure can be considered as the basis of the economy of any nation, [ICE, 1996a]. The recognition of this fact justifies why infrastructure provision and renewal has become widely accepted as a critical function of public authorities, as emphasised by Aktan et al. [1996]. The management of the maintenance of bridge structures is a vital part of this task, since these are critical elements of the transportation network which have a important role to fulfil [Tonias, 1995].

As will be discussed throughout this work, authorities in charge of the maintenance of bridges must administer wisely the usually scarce financial resources at their disposal, prioritising needs and attending to them in the most efficient way. A structured management process, as described in chapter 2, is necessary to support these activities.

The basic aim of the Bridge Management process today is to ensure that the chosen course of action represents Value for Money, as explained in chapter 4. Since value is a subjective commodity, this means that the choice of the most appropriate strategy will depend on the underlying system of values prevalent at the time of decision. This thesis will demonstrate that various objectives are usually being pursued simultaneously and that a utility function should be used to express the interrelation of the various impacts affecting the value of a certain Bridge Maintenance strategy. It will also emphasise that social benefit-cost analysis is normally the most appropriate technique to compare alternatives for investment.

To help bridge managers deal with the complex problem of Bridge Management this thesis will argue that there is a need for the production of a new generation of computer tools. A framework for the development of what will be denominated Advanced Bridge Management Systems will be discussed and an outline of an exemplar of such systems, characterised by a new and flexible architecture and incorporating a new appraisal model, will be developed.

1.1.1 Basic Concepts and Terminology

It is important to introduce some basic concepts and clarify the nomenclature to be used in this thesis. As explained by Aktan et al. [1996], common terminology with a clear definition is a prime requirement for developing uniform research and applications leading to adequate methods and tools for the management of Bridge Maintenance. To start, the meaning of the concept of Bridge Maintenance is not related to the ordinary activities, like painting or cleaning, which usually would be qualified as maintenance activities in the narrow sense. Instead, it encompasses the whole set of activities - maintenance, repair, rehabilitation and replacement - undertaken during the operation of a bridge in order to preserve the condition of the structure over time. Eventually, improvement actions may also be necessary to ameliorate the condition of a structure or ensure that it conforms to new or prevailing requirements. Because this nomenclature can be misleading, in the context of this thesis the combination of all possible actions for maintaining, restoring or bettering the condition of a bridge will be denominated MRI actions, with the acronym standing for Maintenance, Repair and Improvement.

The various activities involved in assessing bridge conditions and selecting a MRI strategy compose the process usually known as Bridge Management, which will be discussed in chapter 2 where a suggestion of a process model for it is presented. The analysis of the elements of the model indicates that the decision-making activities necessary to determine when and how to intervene in each particular structure can be considered as the core of this process.

Decision-making in BM is concerned with the determination of an appropriate MRI strategy. This is a crucial decision influenced by many different factors. Technical and economical considerations are already commonplace, while social and environmental ones are steadily gaining importance. However, the effective success in managing the maintenance of bridges can be difficult to assess. The aims of Bridge Management are multifaceted and usually contradictory, because of the different expectations of the parts involved.

Bridge Management can therefore be considered as a complex and difficult activity. To make the best use of the data available and the expertise accumulated by bridge inspectors and managers, computer-based specialist systems have been developed and employed as decision support aids in this area. These systems, denominated Bridge Management Systems, employ sophisticated analytical methods to analyse bridge maintenance needs and support what-if exercises considering different MRI strategies and levels of funding. In this way they are able to give bridge managers a better understanding of the requirements and priorities of their bridge stock. The analytical procedures incorporated in these systems must use sound reasoning methods and adequate modelling techniques in order to produce reliable results to support human decision-making. The consequences of bad decisions are generally very costly, since the choice of MRI strategy will normally impact the current and future performances of the structure. This may affect the degree of safety, the level of service provided to users and will probably have consequences on the service life.

1.1.2 Relevance of the Research Theme

The status of Bridge Maintenance has changed significantly over the last decade, evolving from being a secondary or neglected activity to become a priority on the agenda of the majority of transportation agencies around the world. This shift in importance was a result of the recognition, by the authorities in charge, that the deterioration of existing structures originates serious problems with important and far-reaching implications, both in economic as well as in social and environmental terms. It is also a reflection of the fact that sustainability is gaining increasingly greater emphasis [ICE, 1996a] and it has been recognised that road space demand can not anymore be attended by road construction.

In the UK, an Assessment and Strengthening Programme was introduced in 1988 to examine the condition and prepare the network for the coming changes in legislation that will allow 40-ton trucks to use some of the main routes [Brodie, 1997]. The objective of the programme was to assess (and strengthen, if necessary) around 140,000 bridges in central and local government ownership. The programme excluded normal maintenance and was planned to be finished by 1 January 1999, but it fell well behind target during its execution [Parker, 1996a] and there are serious doubts about the possibility of successful completion on time. Based on data from the Highways Agency and Local Authorities, Leadbeater [1997] estimates that the total cost could reach £4 billion. These examples illustrate the significant monetary effects that can be associated with bridge MRI operations.

1.2 Motivation

The problem of infrastructure renewal can be considered as being both challenging and timely [Aktan et al., 1996]. The scenario exposed in the previous section establishes the claim for the adoption of a rational, structured and comprehensive scheme for the management of Bridge Maintenance. It also supports the idea of developing Bridge Management Systems to help managers to adequately assess the condition of the bridge network, weighing different courses of action and determining the best strategy to deal with the problem. The development of feasible ways to advance the current standard of these tools could be considered as the main motivation for the research undertaken in this thesis.

The author believes that the work is opportune because there is a definite momentum for change in the area, as discussed in chapter 6. The demands of society for an efficient scheme for bridge management are intensifying, because the importance of maintaining the existing structure in face of increasing traffic is rising. The inability of existing Bridge Management Systems to cope with some of the less structured aspects of the problem is creating dissatisfaction between bridge managers, as described in chapter 3, and introducing more support for change. At the same time, other factors are creating opportunities for effecting this change. An extensive amount of technical knowledge has been amassed in the last decade in this specific domain.

The interest expressed by the Brazilian and the British central transportation agencies in developing nation-wide Bridge Management Systems was also an important motivating factor. One of the possible benefits of this research work would be to use the findings to improve the Bridge Management System of the city of Porto Alegre, in the South of Brazil. Representatives of the Porto Alegre City Council have already shown interest in the work and some of their bridge engineers have acted as experts for the elicitation exercises carried out in this work. With this in mind, some aspects of the research were focused on the examination of the requirements for the creation and implementation of an Advanced Bridge Management System in conditions similar to those prevailing at Porto Alegre.

The research has a special appeal for the author. A background that includes researches into materials performance and inspection and rehabilitation of structures nurtured the belief that maintenance activities are essential to prevent the transformation of simple defects into serious degradation mechanisms. The author also has practical experience on the topic, having been part of a team that inspected all bridges of the city of Porto Alegre and develop a priority rating system to classify the maintenance needs of the network [Klein et al., 1993] [Gastal et al., 1995].

1.3 Aims and Objectives

The general purpose of this thesis is to contribute towards the development of improved ways to manage the maintenance of bridges, in line with the evolving demands and aspirations of modern society and making the best use of available IT tools. In the pursuit of this purpose, the following aims were established:

a) *To make an evaluation of the status-quo in terms of Bridge Management and Bridge Management Systems, consolidating the knowledge in the area, identifying limitations and shortcomings and justifying the need for evolution;*

b) *Discuss alternatives for developing Advanced Bridge Management Systems, examining a series of potential modifications that could help define the outline of these improved systems.*

c) Investigate the most promising changes, exemplifying their use and demonstrating their viability and usefulness.

In view of these aims, the following objectives were defined for the work:

1. Review the knowledge in the domain, examining issues related to current practices and developing a process view of Bridge Management

2. Discuss the path of evolution and the structure of Bridge Management Systems.

3. Examine the question of decision-making in Bridge Management, deconstructing the relationships between the various parties involved to understand their objectives and motivations and how they influence the decision-making process.

4. Investigate the implications of the adoption of the Value for Money approach in terms of strategy appraisal and discuss the role of Social Cost-Benefit Analysis as the most appropriate technique for economic appraisal.

5. Justify the necessity for the development of a new generation of Bridge Management Systems designed to overcome some of the shortcomings identified in existing systems by users, the literature and experts.

6. Identify the desirable characteristics that a new generation of Bridge Management Systems should present, proposing a theoretical framework for the development of advanced systems.

7. Propose an improved architecture for an Advanced Bridge Management System, investigating the possibility of incorporating recent IT advances. Examine how this new architecture could allow future systems to be more flexible, user friendly and easier to customise.

8. Develop more comprehensive and socially adequate appraisal model, based on an improved benefit/cost ratio and in line with the concept of Value for Money. In the process investigate how to adequately estimate the agency expenditure and the positive and negative impacts of an MRI intervention.

9. Demonstrate the viability of implementing the concepts above by developing an object model of the appraisal sub-system of a generic Advanced Bridge Management System denominated ORIGAMI.

10. Verify and validate the results of the research, demonstrating the viability of the proposals and proving that their adoption could result in a different selection of the bridges to be acted upon and in a more reliable allocation of the budget.

The working assumption that underpins the research is that the development of more efficient computer-based systems, designed to support and enhance the decision-making activities of bridge managers, is one of the best alternatives to achieve the target of increasing the overall quality of the management of bridge MRI operations.

1.4 Research Method

The present thesis could be classified as an exploratory study, as defined by Phillips and Pugh [1987] since it attempts to address a new issue, the concept of Advanced Bridge Management Systems. In the pursuit of this aim, the work followed the methodological framework proposed in figure 1.1.

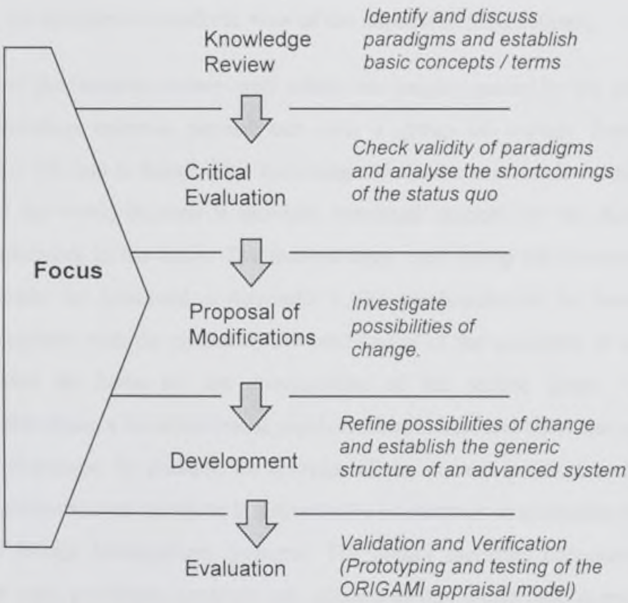

Figure 1.1 – Methodological framework for the development of the research.

The focus of the research was concentrated on the phases of Critical Evaluation, Proposal of Modifications and Development, since these are where the principal contributions to knowledge were achieved in this thesis. Nonetheless, all phases were important in the development of the work, as follows.

As befits any exploratory study, this thesis examined the theories and concepts already in place and used them as the foundation for the development of new ideas. The first phase, *Knowledge Review*, was dedicated to locate and review the accumulated knowledge about Bridge Management and Bridge Management Systems. The analysis indicated that the knowledge in this area is still fragmentary and needs consolidation. A process model was therefore proposed to provide a basis for discussion. The literature review was fundamental to provide basis for the discussion about the aims of decision-making in bridge management. This discussion helped support the argument that Value for Money should be the main policy driver and that social cost-benefit should be adopted as the preferred economic appraisal method. The author went beyond established knowledge by providing a new insight into the objectives of bridge maintenance though the construction and analysis of a soft diagram of the problem and by advocating the adoption of a holistic view of the impacts of MRI actions.

To the results of the literature survey were added the insights gained by the author in knowledge elicitation exercise carried out with a group of experts from local authorities in the UK and in Brazil. This knowledge elicitation exercise is considered a central part of the work, because it provides empirical support for the theoretical discussions undertaken in the thesis. The methodology used during the exercise and a summary of results are presented in Appendix I. The combination of the knowledge gathered from experts with the results of the verification of the capability of existing systems provided the basis for the development of the second phase, *Critical Evaluation*. In this phase a list of technical problems, limitations and shortcomings was compiled and discussed. In parallel, an analysis of the current political and social circumstances demonstrated that there is a favourable momentum to undertake changes in the area of Bridge Management Systems. The author therefore concentrated in identifying the most promising methods and techniques that could help improve the capabilities of the existing systems.

In the *Proposal of Modifications* phase the several paths of evolution for BMSs were examined and it was concluded that various improvements to the current situation were possible. It was decided that some of these changes would be so significant as to warrant the emergence of a new generation of Bridge Management Systems. The concept of Advanced Bridge Management Systems was then introduced and a set of guidelines was suggested to direct the development of these tools. It was also considered necessary to explore how some of the most important of these changes would manifest themselves at practical levels. A combination of Geographical Information Systems (GIS), Fuzzy Logic and Object-Orientation techniques was used to demonstrate how a new architecture for advanced systems could be forged. An improved model for economic appraisal, based on the use of extended Benefit-Cost ratios and the internalisation of external environmental costs, was also proposed. The fourth phase, *Development*, was characterised by the attempt to combine and articulate the various proposals discussed earlier. The creation of a generic advanced system denominated ORIGAMI was proposed. Parts of the system that illustrate the use of the novel system architecture suggested in the work and incorporate the analytical changes proposed were developed. An object model of the appraisal sub-system was defined and discussed. In the last phase, *Evaluation,* a prototype demonstrating the basic capabilities of ORIGAMI was developed and tests and simulations were used to validate the research approach adopted. This effort demonstrated the soundness of the changes suggested and indicated that ORIGAMI could produce meaningful results.

The research was developed in an incremental way, alternating phases of information gathering and knowledge elicitation with conception and development phases, as suggested in figure 1.2. This strategy followed the approach suggested by Nunemaker [1991] and adopted by Ng [1996].

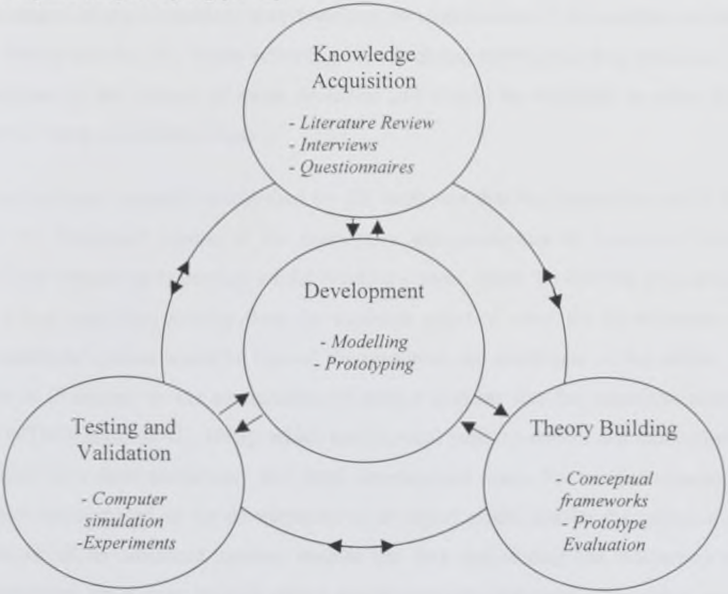

Figure 1.2 – Dynamics of Research (Adapted from Nunemaker et al., 1991).

The overlapping of activities seen in the figure was important to ensure that the work kept pace with the changing reality of the subject under study. The study domain of this work has been very active in recent years, with a great number of research projects being carried out in various parts of the world. The author believes that the research method adopted was successful in maintaining the work up to date and that the findings and conclusions are useful and applicable to real life problems.

1.5 Scope and Limitations

The scope of this thesis, given the extensive and multidisciplinary nature of the research theme, had to be limited. While the process model developed by the author in chapter 2 indicates a series of different activities correlate to support Bridge Management, just the activities related to decision making will be discussed in this work, because supporting them is seen as the most relevant role of modern Bridge Management Systems. This does not mean that there are not important developments to be made in other areas, as discussed in chapter 6. Another constraint is the fact that the discussion about practices, expectancies and decision criteria, as well as the elicitation of expert opinion, were based on the examination of the realities prevailing in Brazil and the UK. While reflecting certain global tendencies, they were just fully analysed in the context of these countries and should be validated to other places before being extended to them.

An important limitation established for the work was that the discussion would focus on the theoretical aspects of the conception and production of improved systems, without attempting to develop a fully working system. Apart the fact that programming is a less significant activity from the academic point of view, the development of a commercial system would be beyond the resources and timeframe of this thesis. This fact is illustrated by the examination of current systems like the American software PONTIS [Golabi et al., 1993], which took several years to evolve and demanded the efforts of a multidisciplinary and large development team. For similar reasons, the thesis concentrated on the development of an object model just for the appraisal sub-system of an advanced system, despite the fact that during the discussion of a framework for change various others possibilities are discussed. The author argues, however, that there are reasons to believe that this is one of the main topics that needs to be addressed in order to improve the performance of existing Bridge Management Systems.

In relation to the validation and verification tests, the intention was to discuss the generic modelling aspects and examine how systems developed based on the concepts proposed in this thesis would perform. The work examines how the new architecture and the improved appraisal model would impact decision-making and demonstrates that it would be possible to create a more sophisticated and natural user interface. A limited prototype was developed to illustrate some concepts but since it was not the objective to produce a workable tool no effort was made to provide it with a full interface or reporting capabilities.

1.6 THESIS STRUCTURE

Chapter 2 introduces the concept of Bridge Management, stressing the important role of bridges and explaining how a discipline has emerged to manage the maintenance and operation of these facilities. The scope of BM is discussed and the stages of the process are examined. In the absence of a consensus about what constitutes Bridge Management a model of how the process could be organised is proposed and the various activities that compose it are examined. Chapter 3 focuses on the role of Bridge Management Systems, describing the capabilities of these tools and discussing their evolution and structure. The establishment of the fact that the main function of these tools is decision support leads to chapter 4, which discusses the fundaments of decision-making in Bridge Management. The recognition of the emergence of the Value for Money policy steers the discussion towards the question of how to assess the value of MRI alternatives. The concept of bridge utility is introduced in this context and a discussion about utility functions is undertaken.

The focus of the work is narrowed on chapter 5, which put emphasis on the importance of economic appraisal in decision-making. The role of economic analysis methods in the appraisal of maintenance strategies is discussed and Social Cost-Benefit Analysis is defined as the most adequate technique to undertake it. The difficulties associated with the monetary valuation of costs and benefits are examined and the implications in terms of valuing the impacts of MRI operations are analysed.

Having established the theoretical background of the thesis, chapter 6 proceeds to undertake an analysis of the technical shortcomings of current systems based on the information available in the literature and on the opinions elicited from experts. The results are combined with a discussion of feedback from users to subsidise the discussion of the limitations of the status quo and establish the need for change. This leads to Chapter 7, where the concept of Advanced Bridge Management Systems is introduced and a framework for the production of advanced systems is proposed.

Chapters 8 and 9 refine the framework, exploring specific modifications suggested to be incorporated in advanced systems. Chapter 8 investigates how certain IT techniques could be used to create a new architecture for Advanced Systems. Object-orientation is proposed to create a modular structure that would introduce a greater degree of flexibility. Approximate reasoning using fuzzy sets and linguistic variables is advocated to model expert knowledge used to support decisions related to MRI strategy definition. Additionally, a GIS component is introduced and placed in the core of the proposed architecture, having in mind the ideas of creating friendly interfaces, incorporating spatial analysis capabilities and facilitating the integration with other infrastructure management systems. Meanwhile, chapter 9 focuses on a proposal for the development of an improved economic appraisal procedure to be used in advanced systems. The emphasis is on an extended assessment of the impacts of MRI operations. A new model is introduced to make a financial appraisal with greater social and environmental awareness. A review of the way agency expenditure is calculated is undertaken to support the model.

The vision of how a generic ABMS incorporating these changes would work is presented in chapter 10. Some of the main components of an advanced system denominated ORIGAMI are discussed and the object model used to support its development is presented and analysed. Chapter 11 contains an empirical evaluation of the various concepts proposed. It checks the general concept of ORIGAMI against expert opinions and validates the improved architecture and the novel appraisal model through simulations and tests, demonstrating how the would impact the definition of MRI actions and the prioritisation of MRI strategies. Chapter 12 contains the conclusions and a series of recommendations and suggestions for further work. The findings of the work are reviewed and checked against the initial objectives. Some aspects related to the translation of the concepts developed into practice are also analysed, trying to offer some insights about issues related to the actual implementation of Advanced Bridge Management Systems.

Chapter 2

Fundamental Aspects of Bridge Management

2.1 Introduction

This chapter contains a review of the general knowledge on the subject of Bridge Management and serves as a theoretical foundation for the discussions carried out in the next chapters. The important role of bridges in a Transportation System is discussed and the criticality of preserving their Transportation Function is emphasised. The significance of Bridge Maintenance is highlighted and the emergence of the discipline of Bridge Management to help support it is described. The scope of Bridge Management is then defined and it is proposed that it could be segmented into four basic stages. A breakdown of the activities occurring in these stages is considered necessary to understand the intricacies of the Bridge Management and the author develops a graphical representation of the process using a well-known process modelling technique. The process is decomposed into 16 activities and the main constraints and resources necessary to its execution are described. Each of these activities is then discussed in order to provide some insight on its role in the overall process.

2.2 The Role of Bridges

"Three things make a nation great and prosperous, fertile soil, busy workshops and easy conveyance of people and goods from place to place" (anon).

According to the ICE [1996a], Infrastructure is the skeleton that supports the contemporary way of life, being composed of "all things physical that are for the use by the population as a whole, not by particular individuals". The collection of the various infrastructure elements of a nation comprises what can be designated as the Infrastructure System. One of the most important parts of an Infrastructure System is generally the Transportation Network (or Transportation System), especially the surface transportation modes – roads and railways. As explained by Halden [1996], an efficient infrastructure of transport is an essential component of a developed economy. The significance of an efficient transportation network can be exemplified by the fact that, in Brazil, more than 70% of the movement of goods and people is made by means of surface transport [Weissman, 1993]. Road transport is also the predominant mode of freight transport in the UK, being responsible by 63% of the 212 billion tonne-kilometres moved in 1993, with a further 6.5% being moved by rail [Royal Commission on Environmental Pollution, 1995].

Highway System is a term sometimes used to represent a subset of the Transportation System formed by the various components that constitute the highways, such as pavements, earthworks, bridges and signalling elements [Markow, 1995]. The importance of Highway Systems in the economic performance of nations is exemplified by Cooper and Munley [1995], who affirm that the continued economic strength and growth of the United States could be intimately linked to the strength and reliability of their highways and bridges. The set of bridges, i.e. the Bridge Network or Bridge Stock, can be seen as the most important component of a Highway System, because they have a unique and important role to fulfil. According to Tonias [1995], bridges are essential structures whose function of establishing vital links in a transportation system can not be overestimated. Any bridge, even the small ones that are hardly noticed in the visually polluted urban environment, has an important role to fulfil. Sometimes they carry a major road or railroad over a difficult spot that would otherwise prevent the passage of vehicles. In other cases they increase the flow of traffic in inner cities or highways by allowing a vertical superposition of traffic passageways. This constitutes what will be denominated in the present thesis as the Transportation Function of a bridge.

All efforts should be made to support and preserve the Transportation Function in order to justify the investment made in the construction of the structure and avoid the serious problems with far reaching consequences that generally result from its interruption. The inability to maintain the traffic flowing increases user costs, penalises surrounding routes with extra traffic, augments the emission of pollutants and tends to increase noise levels. The negative effects are magnified by the fact that normally there are not many alternative routes available in case of closure or restrictions of use of a bridge structure. Consequently, long detours may be necessary and heavy congestion is usually inevitable. These undesirable effects are inversely proportional to the importance of the transportation link carried out by the bridge. They are therefore especially significant in structures that occupy strategic positions in the network, with no feasible alternative offering a similar service in the vicinity. However, small bridges can also be important, especially where the density of the transportation network is low. The loss or restriction of a structure in these circumstances means that a large area might become inaccessible by road or that very long detours might be necessary. This could generate strong social and economical effects, sometimes affecting the economies of whole regions.

Deterioration gradually compromises a bridge and affects its performance. It is necessary therefore to repair, but repair activities will generally disturb the Transportation Function. To obtain good results in defining the best strategy for the bridge network it is necessary to analyse a great amount of data and maintain control over the condition of each individual structure. A sound management scheme needs to be in place to support this effort. This is a vital task because of the great economic and social significance of bridge maintenance activities, as seen below.

2.2.1 Significance of Bridge Maintenance

The economic significance of Bridge Maintenance can be exemplified by examining data available about the conditions of the bridge stock in the United States [Dunker & Rabbat, 1995]. According to Cooper and Munley [1995], the annual cost to maintain the overall bridge conditions of the American bridge stock over time was estimated at approximately \$5.2 billion. The additional cost of repairing all the backlogged deficiencies that were diagnosed until June 1992 would reach \$78 billion. To maintain the condition of the bridges and eliminate the backlog in ten years it would be necessary to expend around \$8.2 billions annually. Apart from the pecuniary implications, the adoption of such a policy would mean the necessity of intervening in

12,000 bridges per year, on average, which would certainly constitute a logistical challenge. The fact that older bridges form a significant proportion of the bridge stock in the United States can be seen as one important factor that accentuates the dimension of the maintenance problem to some extent. Having made this distinction, however, other countries face similar realities and challenges.

Beyond the obvious financial consequences of the expenditure with MRI programmes on government spending and taxpayers, Bridge Maintenance has also a marked social importance. The rapid and continuous growth of car usage amongst the population implies an increasing demand for more capacity. However, concerns about the ecological impacts of great civil works allied with a shortage of funds restrain considerably the possibility of attending this demand through the construction of new structures. The UK Government has already declared its intention to reduce the pace of construction of new highways [NCE, 1997b]. According to Simon [1996], the spending on the motorways and trunk roads in England and Wales was expected to drop 27% in the space of five years (from £2.13 billion in 1994-95 to £1.56 billion in 1998-99). The pressure from society made new resources available and a rise has been recently announced by the Treasury, with the spending in transport expected to rise around 50% from 2.68 to 3.67 billion [HM Treasury, 1998]. According to Marston [1998], however, the increase in expenditure is not sufficient to attend the repressed demand and the scenario of backlogged works should continue. Given this scenario, the criticality of maintaining the existing network in a satisfactory operational condition will tend to increase, as discussed by Bly [1996]. In the absence of the provision of new roads, the public will demand that the existing facilities offer a fluid traffic flow, while still being reliable and safe. Failure in attending these expectation will certainly generate dissatisfaction, which is always aggravated by the unpleasant effects associated with the resulting congestion, ranging from time delays to increases in the emission of exhaust fumes. In view of these facts, the avoidance or minimisation of congestion is becoming one of the most important factors to which Bridge Management should conform. Monetary savings or expediency are in some cases being sacrificed with this objective and, in a recent spending review [HM Treasury, 1998], one of the main policy aims established was the reduction of congestion. In response to this pressing reality, the share of Bridge Maintenance activities has been increasing steadily and this trend is expected to grow. Due to the sensitivity of users to these variations in the level of service, MRI activities must be carefully planned and very well timed to ensure that the benefits deriving from the intervention compensate for the disruption of traffic caused. Bridge Management Systems were created to facilitate and support this evaluation. However, the author will demonstrate that wholesome changes will be necessary to generate systems capable of effectively helping bridge managers to deal with this ill-defined problem. This thesis was motivated by the notion that there is currently enough technical knowledge and reliable tools to allow advances in this field. The recognition of the need for a structured approach to the management of bridge structures over time gave origin to the development of a whole discipline that is currently known as Bridge Management, as discussed below.

2.3 Emergence and Characteristics of Bridge Management

According to Ben-Akiva et al. [1993], Infrastructure Management is the process by which agencies monitor and maintain built systems of facilities, with the objective of providing the best possible service to users, within the constraints of available resources. The case of bridges can be seen as one of the most suitable examples of the importance of using a systematic approach to deal with the management of infrastructure elements. Bridges are essential transportation links and must be carefully administered in order to ensure an adequate performance of the whole highway system. Over the last two decades, the complex task of dealing with the requirements of hundreds and sometimes thousands of bridges deteriorating simultaneously has gained increased prominence and importance [Tonias, 1995]. The need to rationally decide which MRI activities to conduct on these structures has given origin to a great number of studies dedicated to develop tools and procedures to facilitate the management work. The continued interest on the subject has generated the momentum for the establishment of a specialised field of expertise known as Bridge Management.

2.3.2 Definition of Scope

Many authors have discussed the subject of Bridge Management, such as Sriskandan [1991]; Gordon and O'Connor [1992]; Shirole et al. [1993] and, more recently, Chase [1995]; Romack [1995] and Silva Filho et al. [1996]. However, the breadth of activities encompassed by this concept has not yet been clearly defined. A possible reason for this could be the difference between the theoretical and the practical views held about the scope of the process. According to the OECD [1992], Bridge Management should be concerned with all activities from the moment of construction to the replacement of a particular structure. Following this line of thinking, bridge managers would expect to be involved with the supervision of all actions during the lifetime of a bridge, starting with the inception and planning of a new structure and through the asset service life until its de-commissioning. Figure 2.1 shows a representation of this view of Bridge Management as enveloping the asset life cycle.

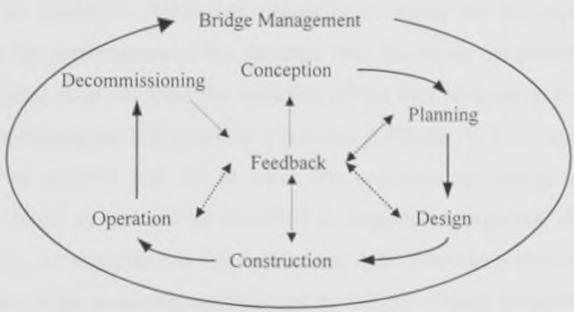

Figure 2.1 – Theoretical view of the scope of Bridge Management.

The management scheme usually adopted in practice is not as comprehensive as suggested by the figure. This derives from the fact that the bridge lifecycle is frequently decomposed in two distinct phases. The first phase is constituted of all pre-construction (conception, planning and design) and construction-related activities. These activities occur just once, in the beginning of the structure's lifetime. They are performed by different parties (usually specialised contractors) rather than the ones that will be involved during the operation of the structure (bridge managers employed by local authorities and third-party specialist maintenance contractors, in general). This dissociation is usually reflected in the management scheme adopted, with a gap being created between the responsibilities for the construction and maintenance activities. The practical scope of Bridge Management is therefore usually limited to the operation phase of the structure, as verified in the behaviour and attributions of the majority of authorities in charge of the maintenance of bridges. This remains true even if it is widely recognised that many problems have their origin in the design and construction stages. Although restricting the natural range of the management process, the delimitation of the concept brings some benefits in terms of reducing complexity.

Therefore, despite supporting the efforts of some authors such as Branco and Brito [1996] that are trying to integrate the management process through this divide, the present work will adopt the restricted view of the process. The nature of these activities composing this process is discussed below.

2.3.2 Basic Stages and Cyclical Nature

The activities involved in maintaining a bridge in adequate condition can be divided into four stages, as represented in figure 2.2. It is necessary to examine the structures and detect the problems. Then it is necessary to assess the consequences of these problems in the performance of the structure and determine the probable degradation curve. The third stage involves the selection of the best alternative to deal with each problem, prioritising the interventions if necessary. Finally, it is necessary to prepare a programme of projects and act to solve the problems according to the priorities established. These stages will be classified as diagnosis, prognosis, therapy selection and treatment. As suggested in figure 2.3, they take place in a cyclical way because bridge structures are rarely decommissioned at the end of their design service life. The management effort becomes therefore an open-ended process, with no definite end.

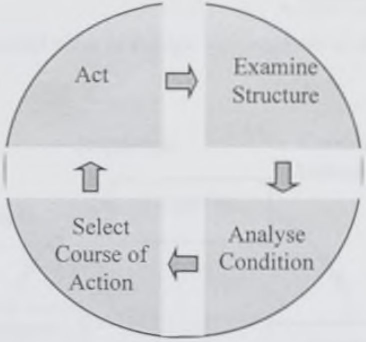

Figure 2.2 – Basic management activities of the Bridge Management Process.

It was considered necessary to expand these four stages to give a more detailed representation of the activities involved in Bridge Management. Unfortunately, there is no standard definition of the steps that should compose Bridge Management in the literature. From the examination of the bibliography available and the scrutiny of the practices commonly adopted by authorities in charge of Bridge Maintenance, the author was able to establish an initial list of activities that could be considered as representative. This list is presented in figure 2.4. To corroborate the list of activities the figure was subjected to experts for comment during the Knowledge Elicitation Exercise discussed in chapter 1. The results indicated that the experts consider this decomposition to be consistent with their own impressions. Having collected the opinion of the experts about the activities forming the bridge management process, a more formal treatment was considered necessary to define the relationships between these activities and examine the constraints that act over them. Therefore, the author decided to use one of the available modelling techniques to create a process-oriented view of Bridge Management. Next section describes this undertaking.

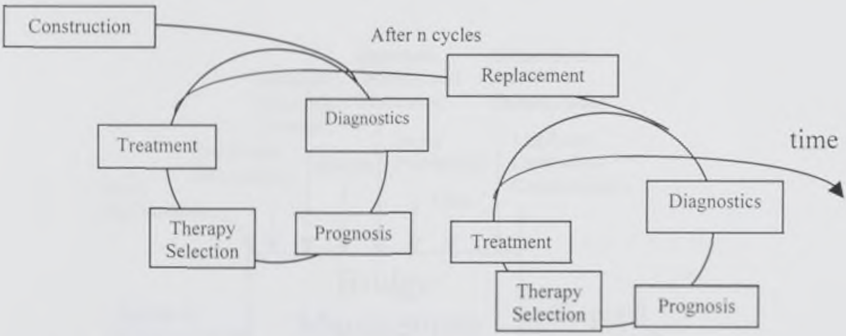

Figure 2.3 – Cyclical view of Bridge Management as an on-going concern.

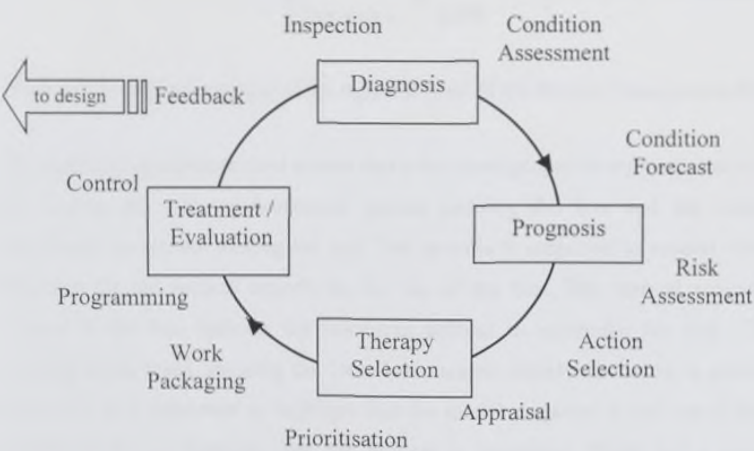

Figure 2.4 - Representation of activities composing Bridge Management.

2.4 Developing a Process Model for Bridge Management

The subset of the Standard Analysis and Design Technique (SADT) denominated IDEFO was chosen as the technique to be employed to model the process. This approach has been recommended by McGowan and Bohner [1993] and has been used previously by Yusuf [1998], which considered it as a very adequate way to decompose activities and model their relationships. Figure 2.5 contains the uppermost level of the model developed. It shows a graphical representation of Bridge Management as a process that receives as input a request to produce a MRI strategy and produces as the output the desired strategy.

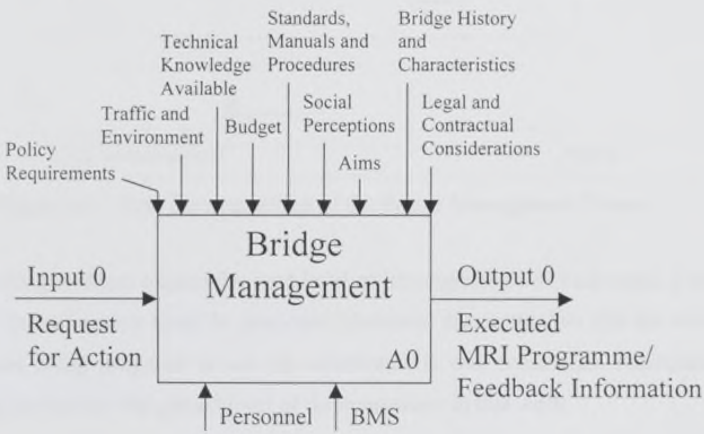

Figure 2.5 – Representation of the topmost level of the Bridge Management Process.

The graphical symbolism used means that a box is employed to represent each activity. The inputs are seen as horizontal arrows entering the box and the outputs are represented as arrows leaving the box. The process is subjected to several constraints indicated by the vertical arrows on the top of the box. The vertical arrows in the bottom of the box indicate the resources utilised to undertake the task. The first decomposition level, showing the fours basic stages already discussed, is presented in figure 2.6. It is important to highlight that the model proposed is just one of the many possible ways to illustrate how the process is organised. While not a universally accepted representation of the problem, the model nonetheless gives a fair account of which activities compose Bridge Management and how they relate to each other.

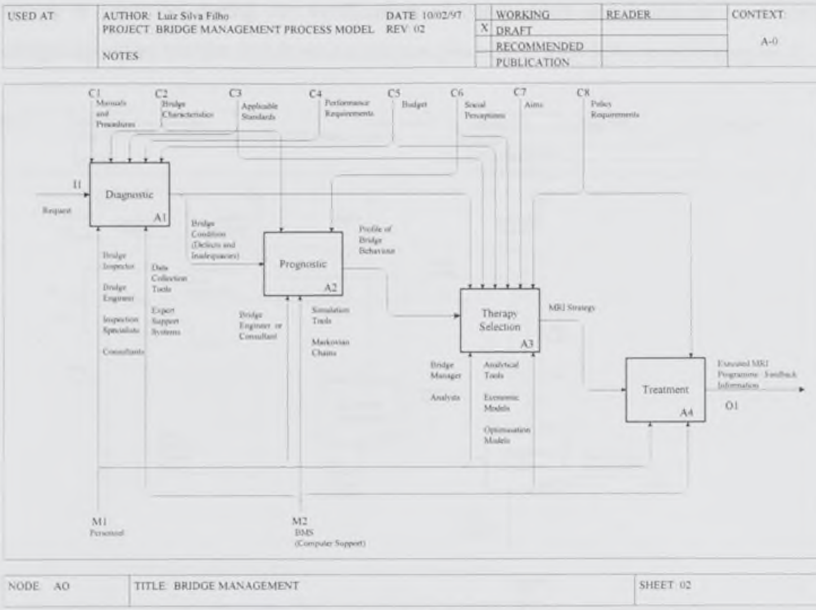

Figure 2.6 – First Decomposition of the Bridge Management Process.

The following sections present the next level of decomposition of each stage. Further levels of decomposition could be proposed. However, due to the fact that the view of the process being proposed is not yet established it was considered inadequate to attempt to go beyond the second level of decomposition in this work.

2.5 Decomposition of the Diagnostics Stage

The diagnostic stage is composed basically by three activities: inspection, condition assessment and verification of compliance, as seen in figure 2.7. These activities provide the factual basis for the whole management process. Having received as primary input the request for analysis, the activities of this stage process it and produce as an output a list of bridge problems due to deterioration or inadequacies. The main constraints are the budget and the technical standards. The inspection activity is constrained by the characteristics of the bridge and the specific manuals and procedures while the verification of compliance can be subjected to performance requirements on the form of level of service standards. The resources necessary include bridge inspectors, bridge engineers and eventually consultants. Computer support is common during the verification of compliance and could be used also during inspection but that is not yet a common procedure, as will be seen in chapter 3.

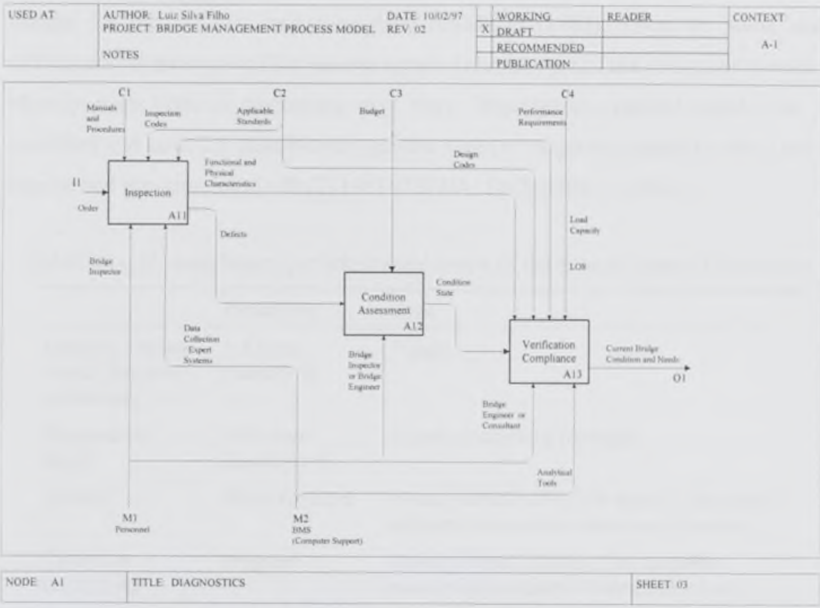

Figure 2.7 - Decomposition of the Diagnostics Stage.

2.5.1 Inspection

Inspections are the basis for any management process involving infrastructure maintenance [Sriskandan, 1991]. The regular examination of bridge structures is vital to provide the data for producing the information necessary to decide whether and what type of maintenance is needed, as discussed by Estes and Frangopol [1997]. However, the concept of regular bridge inspections has just emerged in the late 1960's. Before that records about the condition of bridge structures tended to be scarce and disorganised. Inspection data was just available for special structures, which had greater than usual proportions or presented some other specific characteristic that needed to be carefully monitored.

Regular inspections were first established in the U.S. and can be seen as an indirect result of the Silver Bridge collapse that occurred in 1967 [Lichtenstein, 1993]. In the following year the National Bridge Inventory (NBI) was created to store bridge data

[Turner & Richardson, 1993] and the National Bridge Inspection Standards (NBIS) were established to define the frequency and procedures for inspection [FHWA, 1988]. Standards for inspection have since proliferated in various countries, such as the manual for maintenance inspection from AASHTO [1983]. There are some small differences on the scope of the various types of inspection and the designations used to identify each type of inspection may vary. Nonetheless, general trends can be identified and table 2.1 describes the generic types of inspection usually carried out in Europe and the Americas [ABNT, 1985][FHWA, 1988][OECD, 1992].

Table 2.1 – Nomenclature, periodicity and scope of the generic types of inspection.

	Periodicity	Type
General, routine, visual, frequent, or ordinary	1-3 years (usually 2)	Visual
Principal or major	3-10 years (usually 5-6)	Visual and testing (routine)
Special	When required	Visual, in-situ testing (in-depth). Laboratory tests and assessment exercises (if needed)
Control or monitoring	Irregular	Mainly Visual. Testing if an on-going monitoring program is being carried out
Emergency	After Accidents	Visual and testing (in-depth). Laboratory tests (if necessary). Assessment (usually)

The basic type of inspection is the general or routine inspection, where technicians or bridge engineers visit the bridges and try to identify visually the existing defects. Due to access difficulties it is sometimes necessary to abdicate from the close contact with the structure in favour of using binoculars or other long-range equipment. Some regulations do not allow this, because the absence of close contact can prevent the inspectors from detecting incipient problems and from assessing the real extension from progressive problems. Without close contact it is also much more difficult to assess the severity of the damage. Robots are being projected to minimise this problem. However, this kind of equipment is still in the design and trial stages and time will be needed before they are ready for field implementation. Besides, the complexity and cost of the most sophisticated robots might create a serious barrier to their diffusion.

Major or principal inspections are more spaced and detailed inspections that serve as checkpoints to confirm the findings of the intervening visual inspections. The use of additional test methods is usually compulsory. These methods are largely non-destructive and might include chemical and physical measurements. Techniques used include the determination of chloride and carbonation levels [Bungey & Millar, 1997], the establishment of corrosion rates and the tracing of radar profiles [Colla et al., 1997]. When the regular types of inspection detect an important anomaly in the behaviour of the structure, a special inspection might be undertaken. This might include more sophisticated testing methods such as load testing. It could also require a theoretical verification of the structure, including the re-calculus of the load capacity. In some cases it is considered adequate to control the evolution of certain conditions over time and monitoring or control inspections are carried out. These inspections are also used whenever there is uncertainty about how the structure will perform or when repairs need to be delayed. Finally, the so-called emergency inspections are carried out when an unexpected event that could compromise the performance of the bridge takes place.

A new type of inspection that is starting to establish itself is the cadastral inspection. This inspection is carried out just after the structure is introduced in the system to collect or verify data about the characteristics of the bridge and establish a starting point for the management process. Das [1997a] suggests the introduction of such a type of inspection, to be termed First Inspection, in the new BMS being proposed by the UK Highways Agency.

Proper inspection demands extensive resources. Some bridges can present serious problems in terms of access and the cost of inspection is directly related to this problem. It might be necessary to use special access equipment, specialists trained in climbing with ropes or, as cited before, robots. The provision of inspection facilities during construction can enhance significantly the efficiency of inspections and reduce costs. Unfortunately, while the majority of new bridges are being designed taking inspection requirements into account, the older bridges that form the bulk of the network have not been. The consequence is that the cost of inspection (and maintenance) is normally high. The need for frequent inspections might therefore be seen as almost prohibitive by authorities with little resources. However, prevention is the best way to save money in the long run since the early detection and treatment of problems can reduce the need for much more com plex interventions in the future.

2.5.2 Condition Assessment

The condition assessment step consists basically in recording and defining the importance of the defects identified during inspection, which will characterise the state of deterioration of each bridge element. Aktan et al. [1996] consider that several bridge properties could be used as control parameters to measure the variation of performance over time, such as serviceability, safety, aesthetics, functionality, ease of inspection or lifecycle costs. Whichever the control parameter chosen, the variation in performance is usually represented by a deterioration curve, like the one shown in figure 2.8. This deterioration curve is usually divided into discrete intervals [Vassie, 1997b] to reduce the computational complexity of the analysis carried out to support the decision-making activities [Madanat et al, 1995].

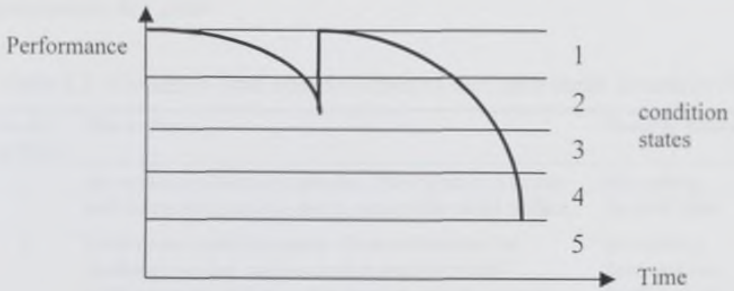

Figure 2.8 – Division of the deterioration curve of a bridge into discrete intervals.

The definition of the number of intervals is a subjective choice. In figure 2.8 five intervals were used, in accordance with the approach adopted in PONTIS, the American BMS [Golabi et al., 1993]. In other systems mores stages are sometimes used. For example, in the Virginia BMS 7 states are defined [Scherer & Glagola, 1994]. Increasing the number of states increases precision in defining the condition of the structure but also increases the computational burden for the deterioration forecast and the optimisation models. To determine the opinion of experts about this topic a question was posed to the practitioners interviewed in the knowledge elicitation exercise discussed in chapter 1. The majority supported the use of five stages, but some of them would prefer a greater number of divisions and suggested the adoption of 8 to 10 stages. The author believes that given that the use of fives stages is well established, provides a reasonable representation of the process and can easily be converted to a decimal basis by the introduction of a mid-stage division, this should be assumed as the standard at this moment in time.

The deterioration stages are sometimes designated as Condition States [Golabi et al., 1993] and the present work will adopt this nomenclature. An arbitrary scale, frequently numerical, is usually adopted to represent these intervals, as was indicated in figure 2.8. Ordinarily bridge inspectors undertake the condition assessment on site, using this numeric scale to define a Condition State that represents the deterioration of an element. The adoption of a clear and well-written description of the expected characteristics of the element in each Condition State is recommended to facilitate the work of classifying the existing defects. Table 2.2 presented an example of such a descriptive scale, extracted from the PONTIS manual and used to grade the deterioration in a girder.

Table 2.2 – Condition State scale for a painted steel open girder as used by PONTIS.

Condition State	Description	Feasible Actions
1	No evidence of active corrosion. Paint system is sound and functioning as intended to protect the metal surface	Do nothing Surface clean
2	Little or no active corrosion. Paint system may be chalking, peeling, curling or showing other early evidence of paint distress but there is not exposure of metal.	Do nothing Surface clean Surface clean and restore top coat paint
3	Surface or freckled rust has formed or is forming. Paint system is no longer effective. There may be exposed metal but there is no active corrosion which is causing loss of section	Do nothing Spot blast, clean and paint
4	Paint system has failed. Surface pitting may be present but any section loss due to active corrosion does not yet warrant structural analysis of either the element or the bridge	Do nothing Spot blast, clean and paint Replace paint system
5	Corrosion has caused section loss and is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.	Do Nothing Major rehabilitation Replace unit

2.5.3 Verification of Compliance

Another step carried out during the diagnostics stage is the verification of compliance. The verification of compliance is usually done against technical standards or level of service (LOS) guidelines. While standards must always be respected, the concept of Level of Service involves the consideration of wider performance aspects and is becoming more emphasised today [Zamborsky & McNeil, 1993]. Basically the idea is to check the conformity of the bridge to some or all of the following factors: load capacity, clearances, deck width and bridge alignments. The non-compliance of an element to the pre-defined requirements gives origin to the need for an Improvement operation. These will have to be prioritised along the maintenance operations. LOS considerations were already present in some of the earlier Bridge Management Systems developed, such as North Carolina's [Johnston & Zia, 1984] and Pennsylvania's BMSs. Despite some initial resistance to this approach [Zamborsky & McNeil, 1993], LOS has progressively started to be incorporated, in one way or another, in a great number of systems, including the Virginia BMS [Allen & McKeel, 1989] and the Finnish system [Soderqvist & Veijola, 1993].

In the UK, the verification of compliance is frequently focused in the structural verification of the load capacity [DOT, 1984] and is usually denominated as Bridge Assessment [Das, 1997c]. Special emphasis has been given to this area in the last few years since, as referred to in chapter 1, a special 15-year programme to assess all bridge to the new 40-ton vehicles was started in 1988 [DOT, 1988]. The majority of major maintenance works being carried out today in the UK is related to the strengthening of bridges that have failed these assessment exercises [Williams, 1997].

2.6 Decomposition of the Prognostics Stage

As indicated in figure 2.9, the Prognostic stage was decomposed in just two activities, Condition Forecast and Risk Assessment. They receive as input the Bridge Conditions and determine what would be the potential evolution of the deterioration and which risk this would imply. This stage is can be considered as an emerging area of Bridge Management. A lot of research has been dedicated to condition forecast methods in the last years and modern systems such as PONTIS have used probabilistic methods to obtain a dynamic view of the deterioration process. The main constraints for the forecast of future conditions are the environmental and physical conditions and available knowledge about deterioration mechanisms and historical trends of deterioration. The later two alongside the user acceptability of risks and the requirements imposed by design and assessment standards act as constrains for the assessment of risks.

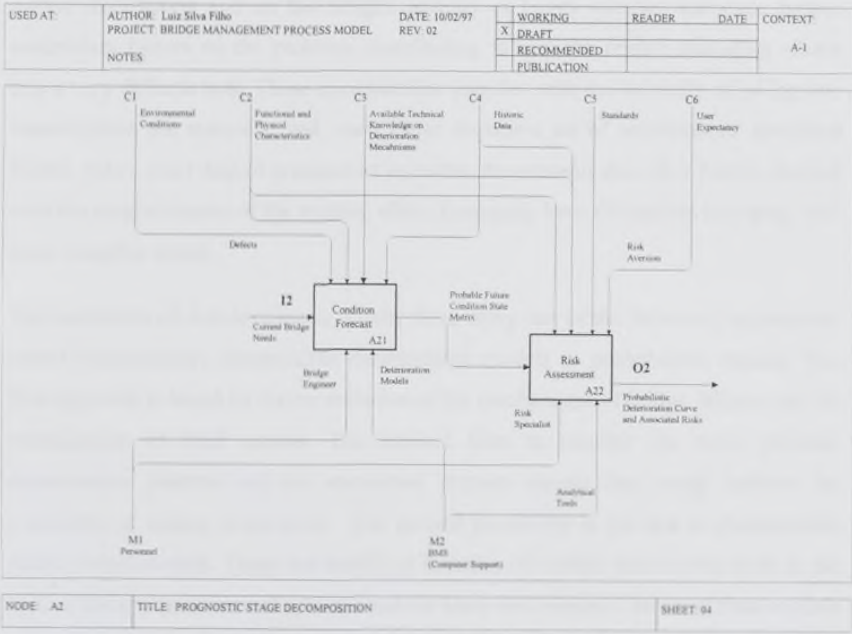

Figure 2.9 - Decomposition of the Prognostic Stage.

2.6.1 Condition Forecast

Condition forecasting is the step of the Bridge Management Process that helps to produce an answer to the question about what would happen if MRI actions were not carried out. This activity aims to estimate the future shape of the performance curve, allowing the consideration of the dynamic effects of deterioration and not just the static snapshot of bridge conditions produced by the inspection. This is becoming an increasingly important aspect because, to make effective use of the techniques of economic analysis based on cost-benefit ratios and whole life cycle costs, it is necessary to be able to assess how the lack of maintenance will affect the future performance of a bridge structure. The lack of knowledge of future deterioration impedes the determination of the option that would minimise maintenance costs [Roskam et al., 1997].

One major difficulty in this process is the unique character of each structure. Bridges present a great diversity in terms of type, material, morphology, age and location. This makes the definition of a general deterioration law or of a single probability of deterioration very difficult, as will be questioned in chapter 5. Changes in the load pattern distribution and on the weight capacity of heavy vehicles introduce further uncertainty factors on the problem, contributing to turn the related managing efforts into a very difficult task. These uncertainties, together with the necessity of taking into consideration the extensive and many times divergent set of requirements discussed before, puts a great deal of pressure on agencies, departments and other bodies charged with the administration of the system, which frequently have difficulties in coping with these complex issues.

The estimation of deterioration is usually done using one of the following approaches: causal relationships; deterministic deterioration models or probabilistic models. The first approach is based on the examination of the mechanisms of bridge failures and the investigation of their causes. The method tries to identify the most probable deterioration patterns and the associated distress signals that could indicate the possibility of failure in advance. The second possibility is the use of deterministic deterioration models. These are usually a function of certain parameters, such as the type of defect, the structural systems and the local environment. Some of these models are the result of multiple regression analysis based on previous data collected, while others try to simulate the deterioration curve. The problem is that deterministic models do not capture the stochastic nature of the bridge deterioration problem and do not provide the decision-maker with a complete description of the possible states of their bridge system [Scherer & Glagola, 1994]. Madanat et al. [1995] discourage the use of deterministic models, arguing that incremental models based on difference equations where the condition at a certain point in time is based on the condition at a previous point are more realistic. Following this trend, the most advanced Bridge Management Systems like PONTIS are adopting incremental models based on a probabilistic approach [Thompson, 1993]. This generally involves the use of a Markovian decision process (MDP) [Cesare et al., 1992] [Ben-Akiva et al., 1993]. This approach consists in the establishment of a Markov chain and the forecast of the deterioration by means of the use of a transition probability matrix [Scherer & Glagola, 1994]. The basic idea is that for each bridge element in a specific environment and in a particular condition state it would be possible to determine a probability to express the chances of it migrating to a worse state or staying in the same state, as shown in figure 2.10. The condition states are used as nodes in the probabilistic chain.

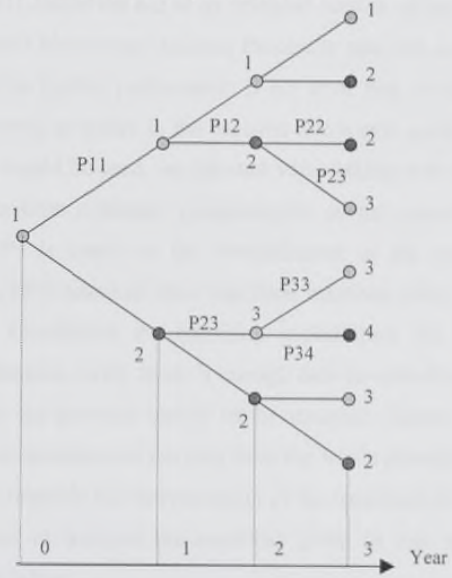

Figure 2.10 – Graphical representation of a Markovian Transition Matrix.

MRI operations would have an opposite effect to the deterioration, improving the condition of the elements. A probability of success in returning the elements to a better state could be established, resulting in the behaviour represented in figure 2.11. As indicated by the figure, leaps of more than one Condition State would be theoretically possible, but they are usually not allowed in current systems.

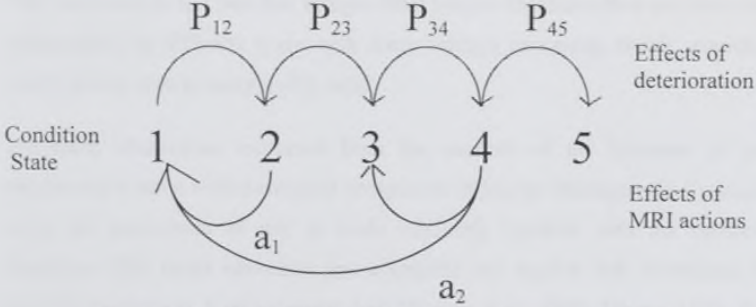

Figure 2.11 – Probabilistic effects of Maintenance and Deterioration.

During a budget interval (usually one or two years), it is generally assumed that there can be a transition just to the next stage.

Ben-Akiva et al [1993] defend the use of an extended version of the Markovian Chains approach, using a latent Markovian Decision Process to take into account the fact that the measurement of the facility performance is not error free. In this case instead of using the condition states as nodes in the decision tree a new parameter denominated state of information would be used, an adjusted value taking into consideration error and additional information available. Independently of the parameter adopted, any approach using MDPs is based on the establishment of the matrix of transition probabilities. Dyer [1989] discusses how transition matrices could be extracted from observations. Often nonetheless the transition probabilities are derived from the opinion of experts, because rarely there is enough data to subsidise the extraction of the probabilities from the previous history of the structure. However, Ng and Moses [1996] advocate the combination of the data from the whole population and the use of reliability analysis to improve the determination of the transition probabilities. This is in line with the need to increase the emphasis given to risk analysis in Bridge Management, as seen below.

2.6.2 Risk Assessment

Risk assessment is the step where the consequences of the existing and the future bridge conditions in terms of the safety or performance of the structure are considered. According to Das [1997b], the management of bridges needs to be based on safety requirements instead of just observable deterioration. Thoft-Chistensen et al. [1996] demonstrated that similar bridges of the same age can have distinct reliability indexes. They point out to the fact that bridges have unique characteristics and can respond to deterioration in different ways with some bridges becoming unsafe whereas others would still be able to carry traffic safely.

The main observation extracted from the analysis of the literature is that Risk assessment is not a well-developed component of Bridge Management Systems. Many times the assessment of risk is made implicitly together with the verification of condition. This thesis advocates that a specific and explicit risk assessment exercise must be carried out. Various researchers [Cesare et al., 1993; Moses, 1996; Estes and Frangopol, 1996, Hearn, 1996] have been studying forms of introducing reliability-based criteria to Bridge Management and this seems a promising area for further developments. One important issue to discuss is the scope of risks to be considered. Apart from the immediate and obvious requirement that drivers and pedestrians could easily and safely utilise the structure in its present condition, all secondary effects must also be assessed. The risk presented by the non-structural deterioration of some elements, resulting sometimes in loose debris that could fall on top of passers-by is one clear example of why the indirect effects of deterioration must be carefully considered.

2.7 Decomposition of the Therapy Selection Stage

As seen in figure 2.12, four activities compose the Therapy Selection stage: action selection, appraisal, prioritisation and work programming. As indicated in the figure, the first three can be understood as forming an iterative looping. One of the main constraints in this stage is the budget. An argument could be constructed for assuming the definition of the budget as one of the outputs of the process. Theoretically, beyond deciding how best to spend the money available, this stage could also include the examination of various planning scenarios to help laymen policy-makers to understand the effects of different levels of financing to the condition of the bridge network. The AASHTO [1992] defends the idea that a BMS must be able to help decision-makers answer questions such as what is the minimum amount of investment to maintain the condition of the network at a certain level and what happens if less money than necessary is available. However, because the definition of the budget is still a political decision in several countries, the budget was assumed as a constraint and not a variable. The changes necessary to alter this assumption are easily made, nonetheless, by the incorporation of an activity that would be denominated optimal budget determination.

The author considers that therapy selection is the stage where the most important decision-making activities take place. It is in this stage that Bridge Management Systems can effectively act as decision support tools, collating the data from the previous stages to apply in simulations to produce a picture of network needs and using appraisal techniques to evaluate possible MRI strategies. Because this stage concentrates the decision-making activities, it will receive most attention in this thesis.

Chapter 4 will be dedicated to examine how decisions are taken in Bridge Management and which factors affect them. Before that a brief description of the scope of the activities in this stage is given below.

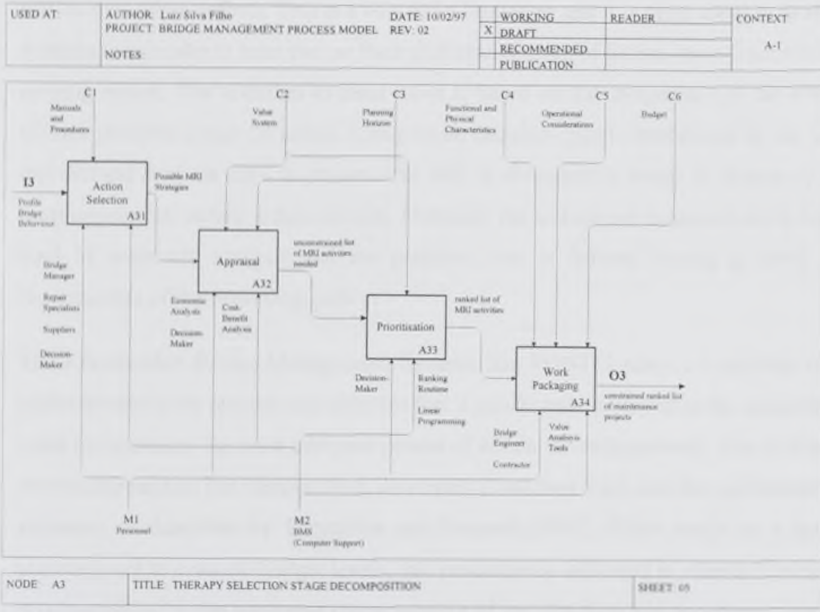

Figure 2.12 - Decomposition of the Therapy Selection Stage.

2.7.1 Action Selection

As described by Obaide and Smith [1994], once a defect has been identified, the key management decision is to determine the subsequent level of intervention, which means to select the type of maintenance action to undertake for each particular bridge element [Vassie, 1997b].

Action Selection can be a difficult task. The number of alternatives is large and is constantly increasing with the arrival of new repair materials. At the same time, there the consequences of the adoption of a certain course of action are not always well determined. The knowledge about deterioration patterns is imperfect and limited, especially where the interaction between defects is taken into account. There are also uncertainties about the effect of MRI treatments and the performance of repaired elements. Additionally, the precise estimation of future demands, the determination of long-term impacts and the evaluation of costs are frequently impossible. In view of these facts, the task of optimising costs over the whole life span of a bridge to determine the best MRI strategy can become a near impossibility [OECD, 1981]. In order to simplify the problem, sometimes a standard action is defined as the unique way to treat some defects. This is a very strict limitation and it is more usual in modern systems to consider at least two or three different courses of action, apart from the do-nothing option. The selection in these cases is based on the comparison of the effects of each possible course of action. Using some decision criteria established by the user and derived from its aims (a process that will be discussed in detail in chapter 4) the most appropriate action is then chosen. Normally the actions are examined using some kind of economic analysis and the preferred one is defined having in mind the requirements of the prevailing policy.

Third Generation Bridge Management Systems like PONTIS adopt a long-term view of the deterioration process and assumes that a steady state policy must be achieved in order to determine the most adequate course of action for each element. The choice of actions depends on the element type, its current Condition State and the environmental exposure, as described by Thompson and Shepard [1993]. While useful as a macro planning tool to evaluate budget levels, this procedure is criticised in chapter 6 because it is insensitive to the particular characteristics of the structure and therefore might be based on incorrect assumptions about the MRI expenditure.

2.7.2 Appraisal

According to Smith [1995], appraisal can be defined as the process of investigation, review and evaluation of the various alternatives for undertaking a project. In Bridge Management, appraisal is the step that provides information to allow the selection and prioritisation of MRI actions. Investing significant sums of money in improving roads requires careful appraisal to ensure that optimum use is being made of the investment [Robinson, 1993]. Appraisal exercises are normally based on the comparison of the positive and negative impacts of an MRI intervention. To perform a proper appraisal, it is necessary to try to include all possible factors. The idea of value as a wide reaching concept representing the balance of impacts will be used in this thesis. As explained in chapter 4, the need for a common basis to analyse the results of the appraisal exercises instigates the establishment of an economic basis for appraisal. It is recognised that sometimes it might be very difficult to express certain factors in monetary terms but the use of valuation techniques as discussed in chapter 5 is recommended if an objective criterion fore the appraisal is desired. Otherwise, a subjective analysis will be necessary.

Economic Appraisal is usually based in some kind of Economic Analysis method. Economic Analysis is described by White et al. [1998] as being concerned with comparing alternative projects on the basis of an economic measure of effectiveness. Benefit-cost ratios are generally the most appropriate measure of effectiveness when the objective is to prioritise projects Mackie [1998a], as is the case during the process of defining MRI strategies under budget constraints. Benefit-cost ratios are usually calculated using the Cost-Benefit Analysis (CBA) technique. CBA is done by discounting the expected future expenditure of each option and determining which one would lead to a reduction on the overall expenditure while ensuring a certain level of performance in the network. The results of the CBA exercise can then be used to subsidise the choice of the best course of action for each element. The results of the economic analysis are also used to define which one of the actions should have a greater priority, as will be explained in greater detail in chapter 4.

PONTIS was one of the first Bridge Management Systems to make use of Economic Analysis. A two-tier model is used in the software. First the recommended MRI action is defined taking into consideration the conditions of the whole network. A limited CBA analysis is then used to provide the basis for the prioritisation exercises. Economic Analysis is seen as vital in the process of decision-making related to defining MRI strategies. As explained in chapter 4, the reduction of MRI budgets and the expansion of Value for Money policies combine to make Economic Appraisal the cornerstone of Bridge Management. This fact justifies the special attention given to it in this thesis.

2.7.3 PRIORITISATION

The initial working assumption used during Action Selection is that all defects will be corrected. This allows the bridge manager to draw an extensive list containing the recommendations for each bridge. The problem, however, is that the authorities in charge of Bridge Management rarely have at their disposal enough money to undertake all the necessary activities. It is therefore necessary to restrict the number of activities to be performed according to the available budget. A prioritisation exercise needs to be carried out to determine which are the actions that should receive greater priority. This is denominated prioritisation and is normally one of the most important steps of the bridge management process.

In older Bridge Management Systems, an arbitrary index was used and the bridges were classified in relation to this index. One of the most notorious examples of such practice was the Sufficiency Index, suggested by the FHWA [1988]. The Sufficiency Index was a combination of various factors divided in three main groups: Structural adequacy and safety (relative weight=0.55); serviceability and functional obsolescence (0.30) and essentiality for public use (0.15). It varies from 0-100, with 100 representing a bridge in perfect condition and zero meaning a failed bridge. More recently, authorities have started to use a cost-benefit ratio instead of indexes to prioritise maintenance actions. This will be discussed in greater detail in chapter 5.

2.7.4 Work Packaging

The work packaging or planning step consists of the creation of MRI project by the aggregation of various activities that need to be undertaken in elements of a single bridge or neighbouring structures. Work packaging is necessary because the impacts on users and the environment, associated with the sometimes stringent conditions that should be obeyed when interdicting a bridge, tend to limit the number of interventions that can be made during a certain interval in the same or neighbouring bridges. No authority in charge of bridge maintenance would like to have to step in repeatedly to solve each one of the various problems usually diagnosed in a structure at the best economical time. It is necessary to have a sensible way to group activities, striking a balance between making the best use of the money and resources available and reducing the disturbance generated by the interventions.

There might also be advantages sometimes in combining activities in neighbouring structures. This approach might lead to a reduction in the cost of relocation of resources and can also avoid the need to disturb the local residents and the users of that specific route. However, political commitments made by the government might constrain the possibilities of combining work. In the UK, for example, there are targets set out in the Annex E of the Road User's Charter [Highways Agency, 1994] that state that 93% of lanes available on the trunk route should be kept available at all times. The charter also states that no two unconnected works inside a length of 6 miles of highway should be executed simultaneously.

Work packaging is not yet an established procedure in the existing Bridge Management Systems. However, this work advocates that the future systems should have the capability of making this kind of analysis, as will be discussed in chapter 7.

2.8 Decomposition of the Treatment and Evaluation Stage

The treatment and evaluation stage will be decomposed in three activities: programming, control of execution and feedback, as shown in figure 2.13. It receives as an input the prioritised list of projects and needs to establish a programme of activities during the budget exercise, control it and pass information about the performance of the bridges during this interval back to the other stages, in order to update the deterioration and cost models.

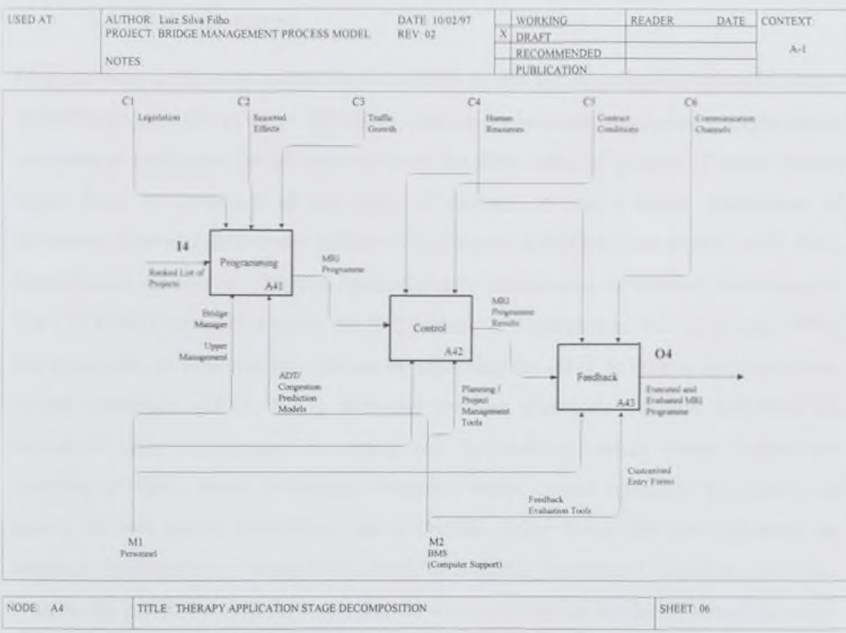

Figure 2.13 - Decomposition of the Treatment and Evaluation Stage.

The main constraints are the legislative requirements and the seasonal effects that act on the programming activity and the human resources for control and feedback. This can be seen as a critical stage, because the control and feedback of the activities are critical to ensure that the MRI programme is effective in bringing an improvement in the quality and performance of the bridge stock. However, since the role of Bridge Management Systems is still small in this stage, less attention will be dedicated to it. This stage receives as an input the prioritised list of projects and establishes a programme of activities to be executed during the budget exercise. It also controls the execution of the programme and pass information about it back to the other stages, in order to update the deterioration and cost models. The main constraints are the legislative requirements and the seasonal effects that act on the programming activity and the human resources for control and feedback. This can be seen as a critical stage, because the control and feedback of the activities are critical to ensure that the MRI programme is effective in bringing an improvement in the quality and performance of the bridge stock. However, since the role of Bridge Management Systems is still small in this stage, less attention will be dedicated to it

2.8.1 PROGRAMMING

Programming is the step where the translation of the list of prioritised projects into a workable programme is done. This step is necessary because in practice it might not be adequate to undertake the projects selected by their order of priority. Certain factors might force an inversion of the order of projects to suit a better distribution of resources. Seasonal effects can influence the impact of MRI actions in the traffic flow. Maintenance during the Christmas period in city centre areas is certainly discouraged. The QUADRO software used by the Department of Transport in the UK [Jones, 1995] has previsions to consider this factors by adjusting the ADT to represent certain non-typical conditions [DOT, 1982]. Seasonal weather variations can also influence the choice of when maintenance is carried out. In colder countries winter months are normally avoided, while in tropical countries works cannot normally be carried out during the wet season because of heavy rainfall. Other factor that can influence the temporal distribution of works is the need for levelling resources to optimise their use. Finally, the predicted cash flow can also be a major factor in the definition of the order of execution of the selected projects.

2.8.2 Control

Overseeing the undertaking of the MRI programme defined in previous steps is the main aim of the control step. The control of execution is vital to verify if the assumptions made during costing and action selection hold true. This information can have an important role in improving the mechanisms used to define the MRI policy that will best serve the user, society and the economics of public governance.

2.8.3 Feedback

Feedback is a vital step that is often not considered systematically. The absence of reliable feedback links can lead to great losses in terms of expertise, since carrying out maintenance allows bridge managers to identify improvements and modifications that could affect both the conception as well as the erection procedures. It is not just maintaining deteriorating structures that knowledge about bridge performance can be gathered. Failures can also provide an important feedback. According to Lee [1991], in the majority of cases the impetus for maintenance seems to come from negative feedback. Major failures tend to play an important role in focusing attention in the bridge maintenance question. As discussed by Cooper and Munley [1995], research on bridge deterioration mechanisms seems to be only conducted with consistence in response to emergencies.

2.9 Summary

This chapter discussed the importance of bridges and introduced the concept of Bridge Management. It established that there is reason to limit the scope of Bridge Management to the operation phase and described the cyclical nature of Bridge Management. Four basic stages were defined for the process: Diagnosis, Prognosis, Therapy Selection and Treatment and Evaluation. The need for a structured view of Bridge Management was discussed and a graphical representation technique was used to generate a process model showing how the four basic stages could be decomposed in a series of activities. The main features of each of these activities were then examined. During this undertaking, the importance of the decision-making activities related to the therapy selection stage was highlighted and the need for computer support was indicated. Next chapter will examine how Bridge Management Systems could be used to support the activities of the Bridge Management process.

Chapter 3

Bridge Management Systems

3.1 Introduction

This chapter presents some basic information about the genesis and evolution of Bridge Management Systems, which are defined as computer-based management tools designed to help in the process of selecting and conducting a MRI programme for a bridge network. Initially, a review of a few elementary concepts related to the domain of Information Theory is made, with the aim of clarifying the concept of what constitutes a Management System. Later, a brief discussion about the important role of computers in the management of infrastructure elements is undertaken, followed by an examination of the path of development of Infrastructure Management Systems from the onset of Pavement Management Systems in the 60's. The natural progression towards systems specialised in Bridge Management is analysed, and the various stages in the evolution of these tools are outlined. Finally, the generic structure of a typical Bridge Management System is examined, exploring the main characteristics of each system component.

3.2 Basic Concepts in Management Systems Development

The rapid evolution of computer technology has brought considerable processing capacity to every desktop. This created opportunities for improving several existing processes since, as pointed by Hopgood [1993], the use of the computer enables a large number of problems to be tackled more efficiently. All human activity fields are striving to learn how best to use this new resource to improve performance. Computers provide a way to carry out routine tasks with more speed, precision and flexibility [Bracken & Webster, 1992]. Specially designed computer systems are being implemented in various domains to increment and supplement human capabilities [BT & Department of the Environment, 1995]. Specialised systems have been developed with the aim of improving the decision-making processes related to the maintenance of the various infrastructure elements, constituting the so-called Infrastructure Management Systems. Some of these were design specifically to help administer bridge maintenance and are commonly denominated as Bridge Management Systems.

Before the characteristics of Infrastructure and Bridge Management Systems are examined in more detail, a brief revision of some basic concepts associated with the field of Information Theory is considered necessary to help define of what a management system usually consists. This revision is justified by the fact that the common usage of technical vocabulary in this domain is sometimes imprecise, due to a lack of a clear definition of certain terms.

Management Systems can be seen as computer-based tools that store data and help to process it into information. The differentiation between the concepts of data and information is critical, according to Martin and Powell [1992]. In normal speech, the words are often used interchangeably, but when referring to computer-based Information Systems it is necessary to make a careful distinction between the two concepts. The notion of data comprises all the measurements and observations carried out in a particular situation, using manual or automated acquisition methods, which could be physically stored. The concept of information is associated with the result from submitting the available data through some kind of organised reasoning process. Data can therefore be defined as a collection of unorganised facts that have not yet been processed into information [Reynolds, 1993]. The transformation process normally consists in a certain reasoning mechanism that by filtering, condensing or aggregating the available data produces the necessary information to support the decision-taking in a certain specific situation. The reasoning mechanism can sometimes consist just in the selection of the relevant data, without further processing. The selected data, if organised in a meaningful way for the user, can already be categorised as information, as pointed out by Date [1986].

The activity of collecting adequate and accurate data forms the basis of any sound management process. However, if a high level of productivity and efficiency is desired, it is information that should flow between the parts of any system since well-structured and timely information will facilitate decision-making and consequently bring a competitive advantage to the organisation concerned. To ensure that the available data is effectively used to produce the desired information available it is necessary to have an adequate Information Management structure [Willcocks, 1994]. The management structure should be carefully planned to ensure that the information relevant to solve a problem is properly produced and flows efficiently to the users in need of it. According to Iliff [1994], Information Management master plans are generally developed to ensure that information is properly handled in an organisation. These plans are usually based on the integration of two elements, Information Systems and Information Technology.

Reynolds [1992] considers that an Information System could be described as a set of structured or non-structured, formal or informal, procedures used to enforce the organisational policies according to the Information Management master plan. As this definition suggests, the concept is not necessarily connected with the use of computer-based applications. Since the 1960s, however, the computing content of Information Systems has grown significantly [Peltu, 1989]. It is not difficult to find instances today where no differentiation is made between computer-based and other less formal types of Information Systems. The association with computers has somehow confused the boundaries of what should be considered an Information System. Some authors use the term to describe the whole spectre of components of Information Management, including not just the procedures but also the people and equipment involved [Reynolds, 1992]. The author will adopt the distinction advocated by Peltu [1989] and separate the use of the equipment from the equipment proper. Accordingly, the collection of equipment, hardware and software that support the operation of an Information System will be considered as a separate entity designated as Information Technology (IT). As shown in figure 3.1, IS and IT are closely integrated components of the general Information Management scheme. In fact, IT will normally be the main support in the implementation of an IS but there will normally be other less formal components in the structure of a typical Information System.

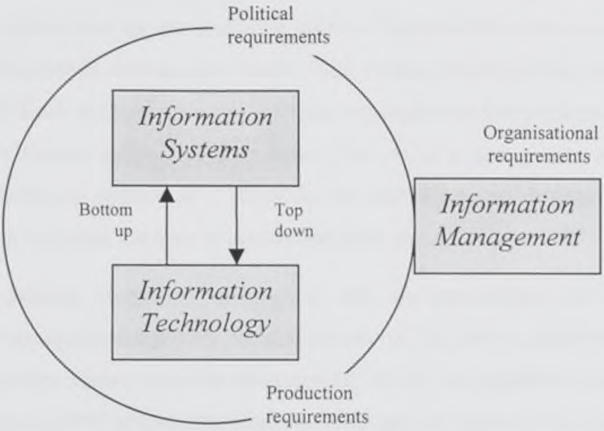

Figure 3.1 – Representation of the Relationships in an Information Management Plan. (Based on Earl [1988] and Iliff [1994]).

Following this idea, in the scope of this research the term Management System will be taken as representing the organised combination of IT and IS elements. This means the embedding of certain procedures and analytical models on a computational environment designed with the specific aim of providing assistance to decision-makers in establishing strategic decisions on the management of infrastructure elements. This thesis will focus on the application of such tools to the specific domain of infrastructure elements, particularly bridges. The role of IT is very important in this field, as follows.

3.3 The Role of Computers in Infrastructure Management

The maintenance and repair of infrastructure elements has been widely considered as one of the most appropriate domains to apply the concept of computer-based Management Systems. Kunt and McCullough [1993] sustain that infrastructure managers require enormous amounts of data to produce the necessary information for their planning, design and construction activities. Tonias [1995] points out that the practical difficulties of managing such massive amounts of data naturally suggest the use of computer assisted methods, specially when dealing with a great number of structures as is generally the case in infrastructure strategic decision-making. Another factor that supports the use of computer-based systems in the infrastructure domain is the complexity introduced by the uncertain nature of some of the data used on the analysis of infrastructure maintenance needs. This makes the production of reliable information a difficult task. At the same time, the constraints on the solution obtained for the problem become more difficult to define. The use of a management system is defended by numerous authors as a plausible and useful way of dealing with the uncertainties that surround this type of decision-making process [Kane, 1993].

The idea of utilising computers to improve the decision-making processes in Infrastructure Management Systems is not recent. It has been considered as a promising possibility almost since the development of the first numerical processing machines. Markow [1995] affirms that Highway Management Systems were among the first applications in the area of civil engineering to try to make use of the then-new technology of mainframe computers. However, the amount of raw data involved and the complex modelling requirements of the problem have placed limits on the usefulness of computers in this domain until recently. The restrictions on processing capacity and the high cost of earlier machines meant that only large organisations were able to afford the systems required to deal with this kind of issue, as discussed by Reynolds [1992]. Significant developments in terms of computer hardware have occurred in the last decade, resulting in a general enhancement in the processing power and in a steep reduction in cost. These factors have induced the popularisation of desktop machines capable of handling large quantities of data and processing it at high speed. These new capabilities have promoted a significant development in the area of computer models used to assist in decision-making. The rapid evolution of technology has enabled systems to operate in ways that would be difficult to envision some years ago [Markow, 1995].

Reynolds [1992] summarises the benefits derived from the use of computers as:

- ability to organise and summarise large quantities of information
- possibility of automate repetitive calculations
- capability of analysing various alternative courses of action concomitantly and quickly, expanding the information available with the possible consequences of present actions

The gradual incorporation of each one of these capabilities can be associated with the various stages of evolution of Bridge Management Systems, as will be seen in item 3.5.2. Peltu [1989] considers that the use of computers has also allowed the co-ordination of the engineering and the management aspects of several management problems, through the development of specialised software that provides tools to consider technical and economic factors together, under a unified set of calculations.

Computers have become especially important in the management of the sub-set of Infrastructure Systems related to Highways. They are now routinely used to keep track of the condition of elements such as pavements and bridges and carry out analysis to help determine which measures must be taken to guarantee their fitness for purpose and continued existence. Next item describes the evolution of some of the most common examples of these tools.

3.4 The Path of Development of Highway Management Systems

The earliest instances of Highway Management Systems can be traced back to the late sixties and the beginning of the seventies, when the term Pavement Management was first utilised, as recorded by Zimmerman [1993]. Pavement Management Systems (PMS) were initially designed to store information about the condition of stretches of pavements. Markow [1995] notes that, roughly at that same time that PMS emerged, design and analysis systems capable of estimating structural capacity and materials properties using elastic or visco-elastic theory began to be developed. The use of these analytical tools facilitated the calculation of stresses and strains at different points in the pavement in response to varying loading conditions and time–dependent changes in the properties of materials. Having the means to assess and forecast deterioration, Pavement Management Systems evolved to incorporate modules to decide which strips of pavement should be rehabilitated first in order to save money and maximise performance. This in time allowed PMS to evolve from data storage tools to assume a more substantive role as decision-support aids and establish a general trend that would be followed by other similar systems.

The simpler nature of pavement deterioration and maintenance when compared with other infrastructure elements like bridges or dams was probably the main reason why this element was the first to receive such attention. The good results obtained with the use of PMS have however led to a continued evolution of Highway Management Systems, as explained by Markow [1995]. Since the popularisation of PMS, a considerable amount of work has been directed towards developing similar tools to other infrastructure elements. Ling et al. [1989], for example, have discussed the topic of sewer management, taking into consideration with special emphasis the external cost implications and the user costs. Kahkonen et al. [1993] in turn discuss the management of the maintenance of power transmission lines. The propagation of management systems to the domain of bridges was a logical step and initiatives to produce a Bridge Management System (BMS) were soon started.

A combination of factors helped focus attention in the area of Bridge Management. This included the recognition of the important role of bridges in a Highway System under growing stress and the establishment of preventive maintenance as a priority to reduce congestion and optimise the use of the existing road system. Reflecting this fact, the majority of the research in the area of infrastructure management systems in the last two decades has been centred in the production of increasingly sophisticated tools to manage the maintenance of bridge networks. As expressed in chapter 1, this is the main interest of this thesis and BMS will be discussed in greater detail in later parts of this chapter. Some of the factors that influenced the popularisation of Bridge Management Systems have also raised interest in related fields. In this decade, applications of the concept of Management Systems in areas such as congestion and traffic management have started to appear. The impetus for this was in great part given by legislation and policy directives that started to appear in the U.S and Europe. The promulgation, in 1991, of the Intermodal Surface Transportation Efficiency Act (ISTEA) in the U.S. can be seen as a major occurrence in this sense. According to Kane [1993], the act amended the United States Code of Highways to establish a new section that deals specifically with Management Systems. The act requires states to develop, establish and implement management systems in five broad areas:

- Highway pavement of federal-aid highways;
- Bridges on and off federal-aid highways;
- Highway safety;
- Traffic congestion;

- Public transportation facilities and equipment.

Since 1995, the US government demands that each state certify annually that these management systems are being implemented. Otherwise, the secretary of transportation may withhold up to 10% of the funds deriving from the United States Code of Highways or the Federal Transit Act, as explained by Kane [1993]. The act is can be seen as a recognition by the authorities of the importance of having an adequate and comprehensive management scheme to deal with increasingly complex infrastructure needs.

In the UK, several policy documents have been dedicated to the consideration of the importance of congestion and environmental impacts and the need for a more comprehensive view of the problems of demand management and road maintenance. The Highways Agency is actively pursuing the development of a comprehensive BMS [Das, 1996b] to help optimise the performance of the road network. Emphasis is given in these documents to the idea of establishing integrated policies for transportation issues [DTER, 1997b].

The political pressure is significantly increasing the interest in the issue of integration of systems dedicated to the management of infrastructure elements, which had already been growing steadily based on technical arguments, as discussed by AASHTO [1992]. There is a growing recognition that additional costs are incurred when infrastructure elements are analysed in isolation and that the existing management structure causes a non-optimal distribution of resources. Wells et al. [1993] advocate the creation of an integrated system, anticipating eventual cost and time savings arising from the unified management of all phases. They report that the Pennsylvania Department of Transportation has already begun efforts to develop a roadway management system incorporating pavement and bridge elements. Markow [1995] sees the consolidation of an integrated management structure as a collateral effect that is emerging from the implementation of the ISTEA act.

The concept of integration has already started to be implemented in a limited way in certain areas. The development of Asset Management Systems can be considered as an application of the ideas behind the trend of integration. These kind of systems aim to deal with all the interconnected physical components of an activity, utilising a unified management structure. Railtrack, the company in charge of the rail infrastructure in the UK, is one of the organisations interested in developing this type of system and the company has manifested interest in adopting a unique maintenance strategy encompassing the track as well as the stations and other physical facilities [Railtrack Interview, 1997].

This kind of initiative will probably be expanded to roads in the coming years, because there is a natural tendency towards co-ordinating the maintenance of the various elements of the road infrastructure. This fact should influence the format and the structure of Bridge Management Systems to be developed in the future. The trend of integration suggests that a much closer relationship will be established between what are today various separated infrastructure management systems. Markow [1995] considers that the hardware and software currently available makes the integration of systems feasible. This vision is shared by the author and will be used as a guideline in the design of the advanced systems being proposed in this work, as discussed in greater detail in chapter 7.

3.5 Bridge Management Systems

Bridge Management Systems can be considered as a particular instance of Infrastructure and Highway Management Systems dedicated to the management of bridge structures. Silva Filho et al. [1995] define these systems as computational data handling and decision-support tools designed to help in developing and implementing a strategy for the maintenance of the bridge network. According to Hudson et al. [1993], the use of a Bridge Management System allow a rational and systematic approach to organising and carrying out all the activities related to the managing of bridges. This is the main justification for their use, as follows.

3.5.1 Justification of use

The problem of decision-making in Bridge Management is a complex one. According to Shepard [1991], bridge engineers have continuously striven to produce better answers to the questions posed by Bridge Maintenance needs, trying to guarantee the functionality and safety of the bridge network in the most economic way. In many cases, however, they have been limited to providing answers based on intuitive reasoning because of the lack of an adequate data handling and information processing system to support the management activities. Apart from the use of certain deterministic calculations to determine the load carrying capacity, the assessment of bridge conditions and maintenance needs is based largely on engineering judgement. This means that decision-making in bridge management is a process marked by uncertainty and that demands continual data gathering and careful analysis. Furthermore, the process is sometimes constrained by the reactive nature of maintenance provision and the difficulties in funding.

There is currently a widespread impression that bridge managers require computer support to enable them to carry out their work efficiently. As seen in 3.3, computers can play an important role in the management of infrastructure elements. Shroff and Nathwani [1995] argue that it is necessary to create a computing environment for the bridge management community that would alleviate the burden of handling data and compiling information. They defend the idea that this could help solve the existing bottleneck in terms of information management and processing that hinders the response to the bridge stock maintenance needs. Additionally, it would have the potential to leave engineers free to perform truly engineering functions. The need for computer support is endorsed by AASHTO [1992], which emphasises in a report on Bridge Management Systems that the analytical capability of an organisation in charge of Bridge Maintenance could be substantially strengthened by the incorporation of decision support tools designed to aid in bridge management. The report concludes that the adoption of such specifically conceived computer systems would be vital for adequately dealing with the maintenance needs of the bridge stock.

3.5.2 Emergence and Evolution

Bridge Management Systems have initially evolved by building over the body of knowledge accumulated in the development of other Infrastructure Management Systems, especially Pavement Management Systems [Zimmerman, 1993]. According to Markow [1995], techniques such as statistical processing, optimisation procedures, multiple objectives prioritisation analysis and knowledge-based and expert decision support systems had already been developed for use in the management of pavements or for the rationalisation of maintenance provision and were quickly incorporated. The greater level of complexity of bridge structures, however, posed new challenges. A bridge is generally composed of several elements, made of different materials, subjected to different micro-climatic conditions and interacting in intricate ways. This presents additional difficulties for the condition assessment and the forecast of deterioration. The development of sophisticated analytical techniques is necessary to cope with these requirements. This fact generated some inertia during the initial stages of development of Bridge Management Systems. Until the early eighties, just two states in the U.S. – North Carolina [Johnston, 1993] and Pennsylvania [Oravec, 1993] - had operating systems of any kind. According to Shirole [1993], the momentum picked up significantly in the nineties, with a significant number of new systems being developed. Initiatives aimed at developing systems were recorded in various American states, such as Indiana [Woods, 1993], Texas [Hudson et al, 1993], Iowa [Fanous, 1995] and New York [Yanev, 1996]. Generic systems like PONTIS [Thompson & Shepard, 1993; Thompson, 1994, AASHTO, 1996] and BRIDGIT [Lipkus, 1993] also started to be developed. During the last few years, studies aimed at finding ways to improve some of the capabilities of Bridge Management Systems were initiated and the evolution of these tools has accelerated.

The tendency for expansion of the number of initiatives for developing Bridge Management Systems was reinforced by the ISTEA act. As discussed earlier, according to the act since 1995 all states in the U.S. have to prove that they are implementing a Bridge Management System to continue to receive federal money. The evolution of systems in the U.S. has stimulated developments occurring in Europe. Some countries, such as Denmark [Andersen & Lauridsen, 1993] with the DANBRO system, have invested a lot of effort in this area. Finland has an ambitious program for developing a sophisticated BMS [Marshall and Soderqvist, 1991]. Less structured initiatives were started in other countries, like Sweden [Lindbladh] and Cyprus [May & Vrahimis].

In the UK the bridge authorities have considered the adoption of PONTIS, but after commissioning a study to analyse this possibility they decided to developed their own system [Highways Agency, 1993]. Research to fulfil this need has already started [Das, 1997c]. Probably the most sophisticated system in operation in Europe today is the Finnish, which was developed under the auspices of the Finnish Federal Road Authority (FinnRA) [Soderqvist & Veijola, 1996]. Alongside PONTIS, it could be considered as an example of a state-of the art BMS. The examination of these systems has provided much of the inspiration for the present thesis. In this work they will be classified as Third Generation systems, as explained below.

3.5.2 Typology

Bridge Management Systems were initially developed to make use of the computer capability of easily storing and manipulating great quantities of data [Vassie, 1996]. These early systems consisted mainly of a simple interface that gave access to some kind of data storage structure containing the characteristics of each bridge and the data generated by the inspections. This type of primitive database-type system will be designated as First Generation Bridge Management Systems (FG-BMS).

Since adequate data management is one of the main building blocks of any effective Information System, even these rudimentary tools were able to make a positive impact in the process of Bridge Management, because they offered an easy and safe way to store and retrieve data. The prompt availability of data allows a swifter evaluation of the needs and constraints of a particular situation by the manager and gives him the capability of instantaneously verify the characteristics and condition of each bridge by querying the database. The swiftness of the process leads to an increase in productivity that can contribute to optimise the use of the usually insufficient staff, condition that seems to be a chronic problem of bridge authorities, as pointed out by some experts during the Knowledge Elicitation Exercise (see Appendix I). This can help produce a more accurate picture of the maintenance needs of a particular bridge, improving the speed and accuracy of the decision-making process. In some systems, the added capability of creating thematic diagrams showing relationship between the data was also a very useful feature.

The fact that data about the characteristics and the conditions of the bridge stock becomes easily accessible because it is stored in a digital media naturally instigates the development of procedures to manipulate this data in order to achieve a better understanding of its meaning. It is possible in this way to produce the adequate information to facilitate the work of the decision-maker, reducing his burden of shifting trough a mass of data to make sense of the situation. Specialised components are usually necessary to transform and deliver data as information to the user, as explained by Deighton and Lee [1993]. As illustrated in figure 3.2, analytical modules were over time incorporated in the existing systems marking the creation of what will be defined in this work as the Second Generation Bridge Management Systems (SG-BMS).

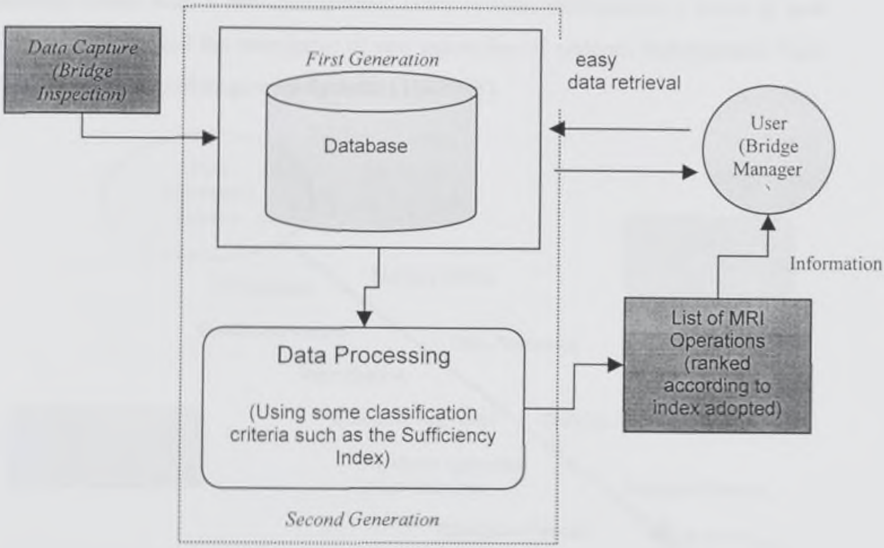

Figure 3.2 - Structure of First and Second Generation Bridge Management Systems.

In Second Generation systems the data stored was used to determine, usually in a simplified way, a scale of priorities for intervention, normally using a simple ranking procedure such as the sufficiency index proposed by the FHWA to determine the relative importance of the maintenance operations needed in each bridge. This provided an easy to use reference to establish network policies. More routines were gradually incorporated in these systems with the aim of improving the amount and quality of the information supplied to the decision-makers. SG-BMS gradually evolved from being mere database management tools with a ranking procedure attached to become rudimentary decision-support tools, offering a valuable service to the limited number of authorities that were making use of them during the late eighties. Nevertheless, the fact that the procedures used were basically arbitrary in nature was much criticised. Moreover, important issues such as the dynamic characteristics of the deterioration processes were not being properly addressed by the second-generation systems.

Realising the potential offered by more developed deterioration models and pressed by the need to deal with the maintenance problem in a more realistic way, a number of countries and organisations has in the beginning of the 90's started to finance or develop system with a new architecture. These systems incorporated a series of new features that marked the emergence of new generation of systems, denominated Third Generation Bridge Management Systems (TG-BMS).

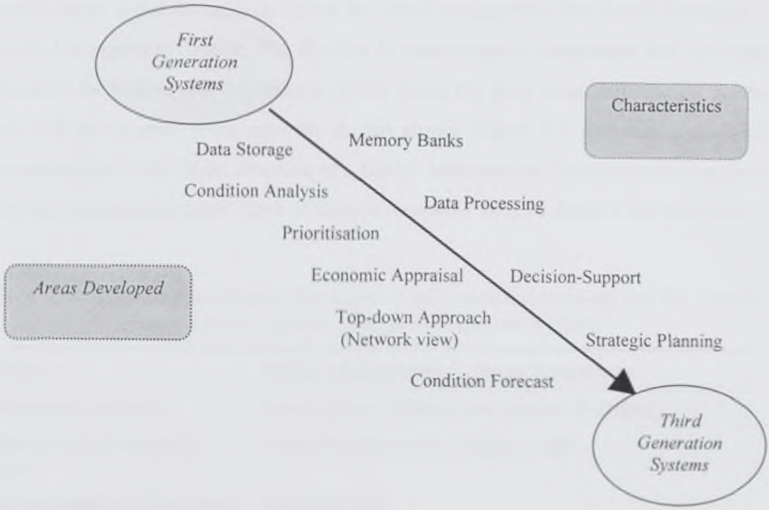

Figure 3.3 – Evolution Pattern of Third Generation Bridge Management Systems.

As seen in figure 3.3, these systems were characterised by the inclusion of modules dedicated to perform a more comprehensive economic appraisal of maintenance options, the inclusion of user costs, the incorporation of the concept of condition states and the segmentation of bridges into elements that have a similar deterioration pattern. One important addition was the introduction of a proper top-bottom approach, instead of perpetuating the limited structure-by-structure analysis. The use of Markovian Chains to model the deterioration, discussed in chapter 3, was also an important modification that brought the concept of probability into the scope of these systems, giving them both a dynamic dimension as well as more flexibility. The Third Generation is the current standard of BMS. A leading example of these systems is PONTIS. The list of aims of a system now include several capabilities that were introduced by this and other leading Third Generations systems. All these various systems nonetheless have certain basic components in common, as described below.

3.6 Basic Components of a Bridge Management System

Kitagawa [1975] defined four stages in the process of transforming data into information suitable for management decisions. Table 3.1 shows how this classification could be used to define the main components that would constitute a Bridge Management System. The division in components is compatible with the ideas presented by Marble and Amundson [1988] about the parts of an information system and will be adopted from now on in this thesis. Figure 3.4 presents a graphical representation of the basic structure of a Bridge Management System containing these four components discussed. Each of them is discussed in more detail in the next items.

Table 3.1 – Relationship between the stages of information processing and the various components of a generic Bridge Management System.

Stages	Bridge Management Systems Component
Production (of data)	Data Capture and Inspection Support Facilities
Storage and Retrieval (of data)	Data Storage (Database Management)
Transformation (of data into information)	Analytical Core
Circulation and Usage (of information)	User Interface and Information Delivery Facilities

3.6.1 Data Collection

Traditionally, the data collection component in a Bridge Management System is very elementary. In the majority of cases, conditions during bridge inspections are hazardous and the access precarious and the inspection data is recorded in paper using standard forms. These forms would be later entered in the computer for storage in a digital inventory. In such cases, the data collection component usually consists just of a simple piece of software used to guide and control the insertion of data the main database.

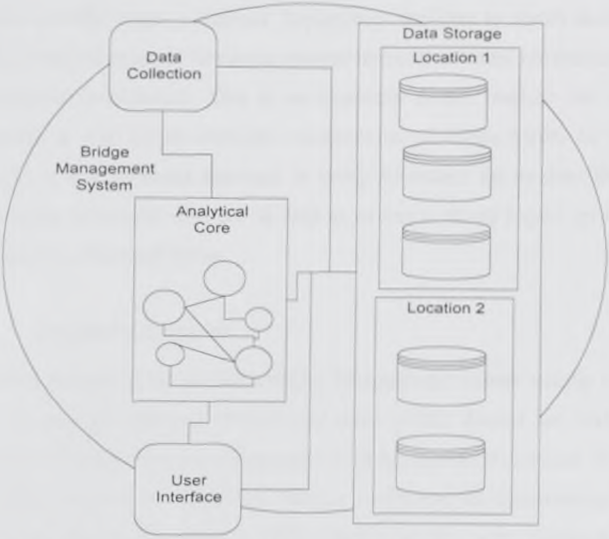

Figure 3.4 – Representation of the components of a Bridge Management System.

Validation clauses are sometimes used to check for the consistency of some input, therefore creating a rough barrier against certain errors involved in handling and transferring of data that could result in its corruption. But not all data is suitable to this kind of control and many errors are not easily detectable using simple acceptance and validation criteria.

In some cases, computers have been used during inspections as data loggers. Data about bridge conditions would be stored in a temporary file that could be downloaded into the main database to be used by the analytical core of the system. The primary advantage of using computers during inspection is related to the reduction of chances of loss or corruption of data during the transmission process from the field to the main office. Paperwork damage; misleading interpretations of field scribbling or diagrams; misplacing of reports and typing errors are just some of the occurrences that could be expected to happen along the repetitive process of entering the results from a series of cyclical inspections in the main inventory. Having the computer available on the inspection site naturally induces the idea of making use of the additional capabilities introduced by this tool to improve the quality of inspection procedures. Electronic forms for data collection can be more flexible, display context-sensitive behaviour and expose a wider range of choices. Explanatory facilities to clarify doubts can also be added. The evolution of computer systems means that visual information can now also be handled comfortably. This is an important factor, because the use of all data available is vital for an adequate consideration of bridge needs. As will be seen in chapter 6, a multimedia approach is being advocated for modern BMSs. This will affect data collection practices as well as having a strong impact on the data storage component, discussed below.

3.6.2 Data Storage

The data storage component of a Bridge Management System usually consists in some kind of database structure. Branco and Brito [1996] discuss the vital importance of databases in infrastructure management, highlighting the importance of having reliable and quick asses to the data about bridge conditions and characteristics. The FHWA data collection manual [FHWA, 1988] emphasises this point, stating that "a complete, thorough, accurate and compatible data base is the foundation of an effective Bridge Management System". This is usually the first component based on which other parts of a Bridge Management System are gradually implemented.

Influenced by the modifications imposed by the U.S. government or due to an indigenous perception of the need for a central record of bridge characteristics and conditions, the majority of countries has developed some kind of electronic bridge inventory. The DISK database established in Holland [Roskam et al, 1997] and the Finnish Central Database [Soderqvist, 1996] can be pointed out as suitable examples. In the UK, the National Archive of Transportation Structures (NATS) plays a similar role. The DISK system [El-Marasy, 1991] is another example of a structured database created to support Bridge Management practices.

Originally, flat files or text files were used to store the data. More recently, relational databases began to be employed [Golabi et al., 1993]. Relational databases can provide a reliable repository structure for the data providing easy access to them and improving the security and the safety against corruption. This is vital because a well-organised database is a critical precondition for the successful undertaking of the complex activities that compose the analytical core of the system, discussed below.

3.6.3 Analytical Core

The analytical core is the heart of any modern Bridge Management System, because it is where all the procedures that transform data into information, saving time and clarifying the situation to the bridge manager, are embedded. Each system employs a different architecture in its analytical core, but there is currently a tendency towards having a main module that administer the activities and a series of customised functions, normally encoded as isolated modules. The majority of Third Generation systems include specialised modules to perform the various Bridge Management activities described in chapter 2. However, some of these modules are not efficient and improvements are necessary, as will be discussed in chapter 6. Using object-oriented technology and the notion of multi-level response, this work will propose taking modularization one step further by creating independent modules that would interact with each but that would be able to perform stand-alone calculations or administer its one data. This will be discussed in detail in chapter 8.

3.6.4 User Interface and Information Delivery Facilities

User interface is the part of a system that users see and interact with [McKelvy et al., 1997]. A well-designed user interface is an important component of a successful Information System [Bracken & Webster, 1992]. It is vital to present the information produced by the analytical core in a format that would suit the user needs, otherwise the whole management exercise might be ineffective since the strengths and weakness of the communication with the user can often outweigh the technical aspects of investment appraisal. What is said and how is said can directly influence the decisions regarding how to invest, especially if the high echelon decision-makers (or policy-makers) are not directly involved in the economic appraisal [White et al., 1998]. In a study developed in parallel to the thesis the author was able to verify that visualisation of needs is seen by all the sectors of the civil engineering industry as the single most important issue to be addressed [UMIST, 1997].

A good interface should include customisable and well structured reporting and querying facilities, which would allow the user to explore or browse the information produced by the analytical core according to his different needs. Visual components can usually play an important role in expressing the needs of the bridge network in terms that are comprehensible and appealing to public decision-makers not familiar with the area. This is one of the reasons behind the proposal for the introduction of a GIS-type interface whose feasibility will be investigated in later parts of this thesis.

3.7 Aims of a Bridge Management System

The OECD [1992] provides a detailed list of specific objectives that should be pursued during the development of a Bridge Management System:

- provide complete, easily accessible and up-to-date archives and documentation;
- allow proper planning of bridge inspection;
- facilitate planning of maintenance work;
- calculate the required budget for both the short and long term (5-10 years), as well as the required manpower;
- facilitate the prediction of the functional economic life of bridges;
- have a mechanism to provide the users with feedback on all disciplines with relevant information acquired from inspection and maintenance experience;
- optimise all processes so that the bridge stock can be managed in the most economical way;
- provide the aid necessary for route choice and recommendation for exceptional convoys;
- provide adequate support for future bridge construction planning and bridge strengthening to meet new standards;
- entitle the systematic follow-up of each activity in the bridge management process

All these objectives are relevant to the role of these tools but according to the OECD [1992] the main purpose of a Bridge Management System is to provide support for the decision-making process undertaken by bridge managers. In light of this consideration, the basic aim of a Bridge Management System could be defined as to help managers identify and prioritise the maintenance and improvement requirements of the bridge stock, while clarifying the technical and economic implications of undertaking or delaying activities. To achieve such objectives a BMS must rely on adequate data collection facilities, a reliable data storage structure, a sophisticated and flexible analytical core and a user-friendly and effective interface as discussed before. The development of more sophisticated systems should not, in the opinion of the author, be directed at substituting the human user, but instead should be aimed at developing tools to help him deal with a comp'ex situation where priorities need to be established between numerous competing and contradictory demands. This is not an easy task and chapter 4 will concentrate on examining how decision-making occurs in Bridge Management.

3.8 SUMMARY

This chapter gave a brief insight on the concept of Bridge Management Systems. The question of what constitutes a management system was clarified and the use of computers to help manage the maintenance of infrastructure elements was justified. The emergence of BMS from Pavement Management systems was described and the important concept of systems integration was introduced. The aims and the basic structure of Bridge Management Systems were discussed and the path of evolution followed by these systems was examined, showing how they evolved from simple data storage structures to sophisticated strategic planning tools capable of dynamic analysis of bridge conditions. The notion that three generations of systems can be identified was presented. Reference was made to some of the main existing systems. Finally, the four basic components that constitute a typical system were described. The main conclusion that emerged from this chapter however is that BMS are decision support tools, that extend the human capability to reason in uncertain terms to allow an structured and objective management of a large number of bridges.

Examination of the Principles of Decision-Making in Bridge Management

4.1 Introduction

Decision-making is considered as a relevant issue in the context of this thesis since it has been established that the main role of a BMS is to serve as a decision support tool. A description of the typical flow of decisions necessary in order to define MRI strategies for the bridge network is presented in this chapter. Some of the basic political and social factors that influence the decision process are then discussed. A soft model is used to illustrate the multiple dimensions of the problem, which result from the conflicting motivations of the parties involved. Special attention is given to the effects of the dissemination of the Value for Money policy. The repercussions of the adoption of this stance in Bridge Management are discussed and the work explains how utility functions can be used to help estimate the value of a MRI strategy. Finally, the role of cost as a common denominator of utility components is examined and this is used as an argument to justify the fact that Economic Analysis has become the preferred approach for the Appraisal of the impacts of MRI actions.

4.2 The Problem of Decision-Making in Bridge Management

Due to natural or anomalous deterioration over time any civil structure develops certain defects that affect and may compromise its performance. In the case of bridges, the exposure to traffic action and environmental factors eventually causes structural or material distresses. Remedial actions are supposed to be taken to solve or minimise these problems and ensure that the desired service life is achieved, or surpassed. These actions may vary in intensity, from simple maintenance activities and minor repairs to major rehabilitation schemes, including in some extreme cases the replacement of the whole structure or significant parts of it, as seen in chapter 1.

The basic conundrum of decision-making in Bridge Management is to find the best combination of actions over time, including the do-nothing option, which would constitute the most appropriate strategy in view of the established (and often conflicting, as will be seen ahead) aims of the process. As referred to by She [1997], it is necessary to establish "when to do what with which bridge". The combination of the most adequate actions for each bridge in the network will be denominated in this work as the MRI strategy.

According to Scherer and Glagola [1994], the definition of MRI strategies is not always an easy task because the decision-making environment in Infrastructure Maintenance is usually very dynamic, involves multiple objectives and is normally subjected to great uncertainties. From a technical point of view, the complex nature of bridge deterioration and the uncertainties of condition forecast exercises introduce a fair degree of uncertainty. The problem is that each bridge has particular characteristics and the variety and synergetic nature of defects create unique deterioration patterns. Additionally, the conflicting interests of the parties involved (and their manifestations in terms of policy requirements) can also change over time, affecting the definition of best strategy to adopt.

Decision-making in Bridge Management can consequently be considered as a process marked by uncertainty and that demands continual data gathering and careful analysis. This chapter aims to investigate the aims and the structure of this process. Next section starts this task by illustrating the typical flow of decisions involved in the definition of a MRI strategy.

4.3 The Flow of Decisions in Bridge Management

Figure 4.1 shows a representation of the flow of decisions necessary to determine the most appropriate course of action to be adopted for each bridge in the network. As seen in the figure, the first decision step is to verify if the bridge is still needed. Otherwise, the action chosen would probably be to demolish. If the bridge is not obsolete but is not compliant with current standards, improvement actions might be needed. If the non-compliance problems cannot be easily solved, it might be necessary to substitute the whole bridge and the resulting decision could eventually be to demolish and replace, as for example in the case of the Bay Bridge in the U.S. discussed by Greeman [1996].

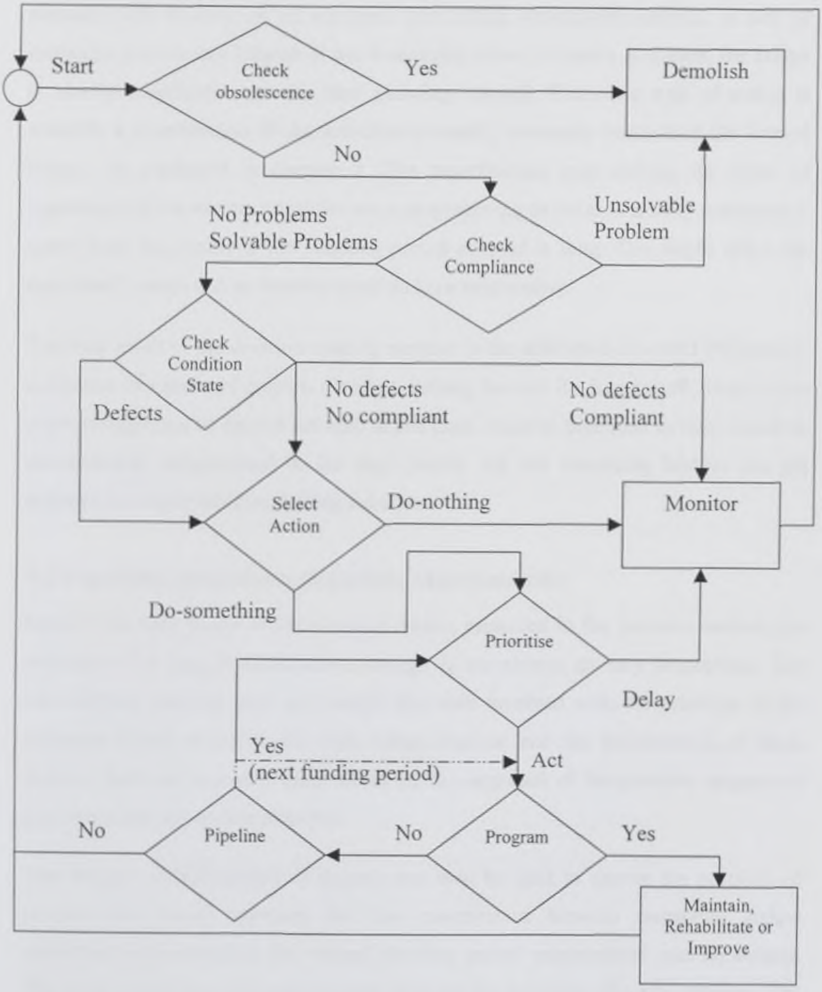

Figure 4.1 – Flowchart of the decision-making process in Bridge Management

In the majority of cases, however, the non-compliance is localised and improvement actions or partial replacements can solve the problem. Maintenance or repair actions might also be necessary, even if the bridge is compliant, because of the natural and progressive deterioration of the structure.

After the MRI needs are identified, the decision about which is the best course of action to follow is taken based on some kind of appraisal of the consequences, which normally will be done on an economic basis using cost-benefit analysis, as will be explained later in this chapter. If the do-nothing course of action is chosen, the bridge is usually monitored until the next planning interval. If another type of action is selected, a prioritisation of the activities is usually necessary because of the limited budget, as explained in chapter 2. The prioritisation step defines the order of importance of the various activities but a programming exercise is usually necessary to space them temporally if the planning period adopted is long. This might affect the cost-benefit ratios and an iterative analysis is recommended.

The final result of the decision-making exercise is the definition of a MRI Programme composed of a series of projects distributed along the next funding period. Some of the projects might not be carried out and, in this case, could be pipelined so they would be automatically programmed in the next period. All the remaining bridges are put together for a new decision-making exercise.

4.4 Strategy definition in Bridge Management

Despite the clear nature of the decision matrix presented in the previous section, the definition of a cogent maintenance strategy is not always an easy proposition. The most critical decision steps are usually the ones involved with the selection of the adequate course of action for each bridge element and the prioritisation of these actions. Both are normally done based on the appraisal of the possible impacts of pursuing a specific course of action.

The analysis of the balance of impacts can then be used to choose the portfolio of projects that would represent the best compromise between respecting budget restrictions and attending the various standing policy requirements and aspirations. The results of this exercise are the main basis for the definition of a MRI strategy. The question of defining a suitable strategy is however complicated by the fact that there are no fixed standards about how to proceed to solve the problems diagnosed during inspection. There is no specific guidance about what to do in each particular situation or when to intervene in a structure. There is also no firm guidance about how different impacts should be assessed and valued. The ultimate decision about the definition of strategies can be influenced by various factors such as the prevalent attitudes towards maintenance, the type of approach adopted and, especially, the decision criteria utilised. The investigation of the circumstances that affect the definition of MRI strategies is an important part of this chapter and a brief revision of each of these factors is made below.

4.4.1 Attitudes towards Maintenance

Policy-makers and public administrators have traditionally tended to see the maintenance of infrastructure elements as an unattractive activity with small visibility and that brings little political return. This low political attractiveness helps to explain why maintenance has been attributed a secondary importance in many places and justifies why Bridge Management has tended until recently to be unstructured and reactive. Apart from emergency situations, when the very existence of the bridge is in risk or an grave accident has happened, it has been a common practice to let bridges deteriorate because of the lack of money and the reduced political interest in maintenance. Bridge managers and owners have often only been driven to action when serious deterioration became apparent [Lee, 1991]. This is the panorama found in many developing countries and Brazil is no exception. Silva [1989] reports, for example, that in the city of São Paulo several bridges were allowed to deteriorate until no more traffic could be carried and emergency action had to be taken.

The delay of maintenance is not a situation confined to the poorer countries, however. Even in developed countries it is not unusual to find inertia towards maintenance. Frequently it is just when users exposed to the effects of poorly conserved bridges start to complain that the authorities concerned are driven to act to solve or minimise the problem. The Automobile Association [1998b] considers that there is a perception between drivers in the UK that bridges often "are not fixed until they become a major problem, leaving motorists fuming in unnecessary traffic jams". Even when the demand for action is well established, the limited budget can prevent a prompt response and the remedial actions sometimes come too late. This was the case, for example, of the Kettlewell Bridge in North Yorkshire (UK), where the continuos postponement of action because of money shortages resulted in the partial collapse of the structure [Bishop, 1993]. A similar situation where the postponement of works was considered unavoidable because of money shortages has been recently reported.

This reactive stance needs to be altered if rational Bridge Management is to be implemented. There are strong arguments for adopting a pro-active stance since there are usually significant benefits in preventing a bridge to deteriorate seriously before being repaired. A reactive stance means that, when the deterioration has progressed to the point of causing enough discomfort to users to generate pressure and trigger maintenance, the optimal moment for undertaking maintenance has usually already been passed. The National Audit Office in the UK has estimated that the delay of repairs actions could cause an increase of up to nine times in the final expenditure [Automobile Association, 1998b]. Fortunately the situation is changing. As discussed in chapter 1, maintenance is gradually gaining prominence due to a greater awareness of the serious social and economic repercussions of the interruption of the Transportation Function. Yet, some aspects still need to be addressed to make this change more effective. It is necessary for example to establish an adequate management structure to co-ordinate maintenance and ensure that problems are analysed correctly and consistently. The lack of good management can be expensive. The Automobile Association [1998b] estimates that at least 15% of maintenance resources are used today in a wasteful way, because decisions are not co-ordinated at local or national level. This thesis advocates that the adoption of more sophisticated Bridge Management Systems can go a long way towards improving this situation. It is also necessary to put at the disposal of Bridge Authorities enough resources to make viable the maintenance programmes established with the aid of Bridge Management Systems. This is a sensitive topic, because users frequently feel that they already pay enough for inadequate service [Automobile Association, 1997].

4.4.2 Project and Network Approaches

Thompson [1993] considers that strategy definition in Bridge Management can be approached from two different perspectives: top-down and bottom-up. The *bottom-up* or *project-level* perspective gives emphasis to the determination of the best treatment to each bridge. An intervention plan is defined by analysing what would be the best strategy to solve the defects diagnosed in a particular structure subjected to certain economic and technical considerations imposed by the user. This implies the adoption of a tactical view of the problem, based on the definition of specific strategies prior to a network-level analysis of needs and constraints.

The AASHTO [1992] argues that it is not sufficient to manage at the project-level because the best action for an individual bridge when considered alone is not necessarily the best action when faced with funding constraints for a whole network. According to them, it is increasingly important to optimise the use of resources over the whole network. The *top-down* or *network* approach adopts a more strategic view of the problem and can be defined as an "hierarchical bridge planning and management techniques that begin with an analysis of network-wide goals and constraints to generate network-wide policies that are subsequently applied to individual bridges" [AASHTO, 1992].

Traditionally, the analyses of bridge maintenance needs and treatments have been carried out on a project level basis and the bottom-up approach is still the most common. But several Bridge Management Systems have already started to adopt a top-down approach, as remarked by Thompson [1993]. This might be understood as an indication that Bridge Management practice is becoming more influenced by the demands of the government, which tends to hold a strategic view of investments and always express the desire to optimise or reduce costs.

4.4.3 Decision Criteria

The most important factor in the decision making process is the definition of the decision criteria. These criteria can be seen as an expression of the aims of the decision process as interpreted by each bridge authority and are used to guide the decision-taking activities. In order to manage bridge structures effectively, a good understanding of the nature and evolution of these criteria is necessary.

As indicated in chapter 3, the first Bridge Management Systems were created to help ensure structural safety and this can still be considered as the fundamental criterion of Bridge Management. The fact however is that the inherent brisk of bridge failures is very low for bridges in average condition [Menzies, 1997] and few bridges actually fail because of overloading or structural deficiency [Parker, 1996a]. The decision process therefore does not need to focus on preventing immediate collapses but instead in finding strategies that reduce the risk and prevent deterioration from reaching dangerous levels. Consequently, there is normally considerable room for manoeuvre and other criteria usually have a more important role. It was verified however that distinct authors harbour slightly different views on what these criteria should be.

Kane [1993] considers that a management system must be able to provide a framework for cost-effective public decision-making while also emphasising enhanced service quality at minimum life-cycle total cost. Kleywegt and Sinha [1992] define the primary aim of Bridge Management as to allocate and use the limited resources available in an optimal way for the provision of service. Silva Filho et al. [1995] consider that the main aim of Bridge Management would be to handle all activities necessary to ensure that the structure remains fit for purpose during the desired service life, under the planned maintenance. Das [1996a] defines the primary aim of bridge maintenance as to maintain the reliability of the bridge stock at an optimum level by forecasting future needs sufficiently in advance and by deploying the best maintenance strategy possible with the available resources. The AASHTO [1992] report on Bridge Management Systems describes the purpose of Bridge Management as to combine management, engineering and economic inputs in order to help determine the best actions to take on all bridges on a network over time.

Examining these definitions and others available in the literature, the author realised that it is possible to identify three basic dimensions to which the majority of current decision criteria are related: cost, safety and serviceability. These are represented in figure 4.2.

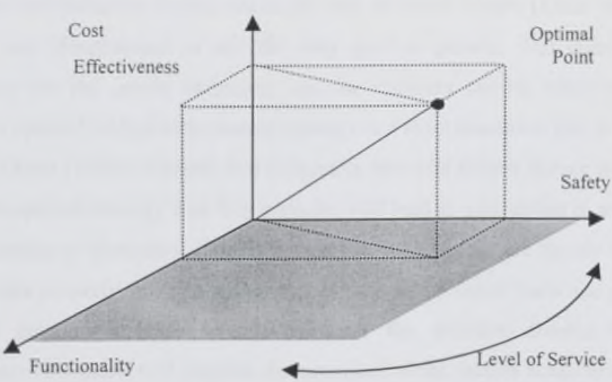

Figure 4.2 – Traditional fundamental dimensions of the Bridge Management aims.

The tendency to favour some of the basic requisites presented in the figure helps to explain the differences observed in the definitions listed before. Kleywegt and Sinha [1992] seemed to favour the cost dimension, while Silva Filho et al. [1995] emphasised the aspects of safety and serviceability. Das [1996a] focused on the structural issues related to safety and made reference to economic aspects, but did not mention the functional dimension of the problem. The AASHTO report gave the most inclusive definition of objectives. Vassie [1997a] adopts a similar view and suggests that "the objective of a bridge manager is to minimise the expenditure on maintenance work subjected to keeping the stock in a safe and serviceable condition".

The three dimensional model seen in the figure is considered to be an adequate representation of the current understanding of the nature of bridge management aims. All three dimensions are normally recognised as important, but the relative importance given to each one of them may vary, depending on the policy adopted or in individual biases of the decision-makers. Indeed, in recent years, the decision-making process in the domain of Bridge Management has become strongly based on economic considerations. According to Thompson [1993], Bridge Management Systems are now being designed as tools to provide assistance for managers to make more informed decisions regarding investments. Andersen and Lauridsen [1993] consider that the main incentive for the development of Bridge Management Systems is in fact to save money by using effectively the usually limited budget. This has been for example the case during the creation of the Washington State Pavement Management System, as interpreted by Jackson [1993] and also provided the motivation for the work on Bridge Maintenance prioritisation carried out in the city of Porto Alegre [Klein et al., 1993]. However, cost effectiveness is not the only goal to pursue. The aims of Bridge Management are not purely economic and the decision criteria must expose that. Pursuing an optimal technical/economic strategy is a strict condition that is not always respected. Vassie [1997a] remarks that frequently practical factors induce authorities to adopt a non-optimal strategy that they consider will lead to a reduction in total costs or the minimisation of disruption. This fact seems to suggest that are factors that are not being consider properly yet. The author agrees with this point of view and proposes to attempt to develop a more holistic view of the decision criteria for Bridge Management. This thesis will propose the extension of the factors considered and their aggregation using a dynamic Bridge Utility function that could be modified according to changing society perceptions.

The first step towards this objective is to analyse the relationships of the various parties of society with the bridge network and try to identify which requirements might not be being attended. Technical priorities do not always reflect the perception of needs held by the general public, and the government many times sways between these two views, while constantly holding a strong concern about cost. To clarify the problem it is necessary to understand what each one of these parties expects from a bridge. The next item proposes a soft model of Bridge Management that might help with this understanding.

4.5 A Flexible Model for Understanding Decision Making in BM

To understand the aims of decision-making it is important to recognise the distinct motivations that drive the various parties of society that are involved with the process of Bridge Management. The particular objectives of the bridge owner, the opinions of users and the society's perceptions about the function and the importance of the structure could all influence in the definition of the aims of the decision process. Due to the complexity of the issue, a "soft systems" diagram was employed to represent the problem. This will hopefully provide a fresh view of the problem, contributing to a better understanding of its complexities.

The diagram was constructed using a "soft" approach because the problem of strategy definition in Bridge Management is bounded by fuzzy constraints and is characterised by the presence of many parties interacting with distinct objectives. Soft systems, as defined by Scholes and Checkland [1990], is an adequate methodology to deal with unstructured problems where the designation of objectives is problematic. It is accepted that soft systems are an interesting approach in situations where the problem can not be reduced in parts for analysis without oversimplifying the situation and loosing some of the existing relationships. According to Scholes and Checkland [1990], this is what usually happens when dealing with what is described by him as "human activity systems". This thesis considers that the problem of Bridge Management can be classified as such.

A diagram representing the various forces in action was developed after a detailed examination of the relationships of various parties with bridges and an analysis of the effects of bridge deterioration on each of them. Later, during discussions with experts the diagram was presented for comments and suggestions. The final format is displayed on figure 4.3. The construction of the diagram was not carried out strictly according to the CATWOE method advocated by Scholes and Checkland [1990], but the general principles of the methodology were respected.

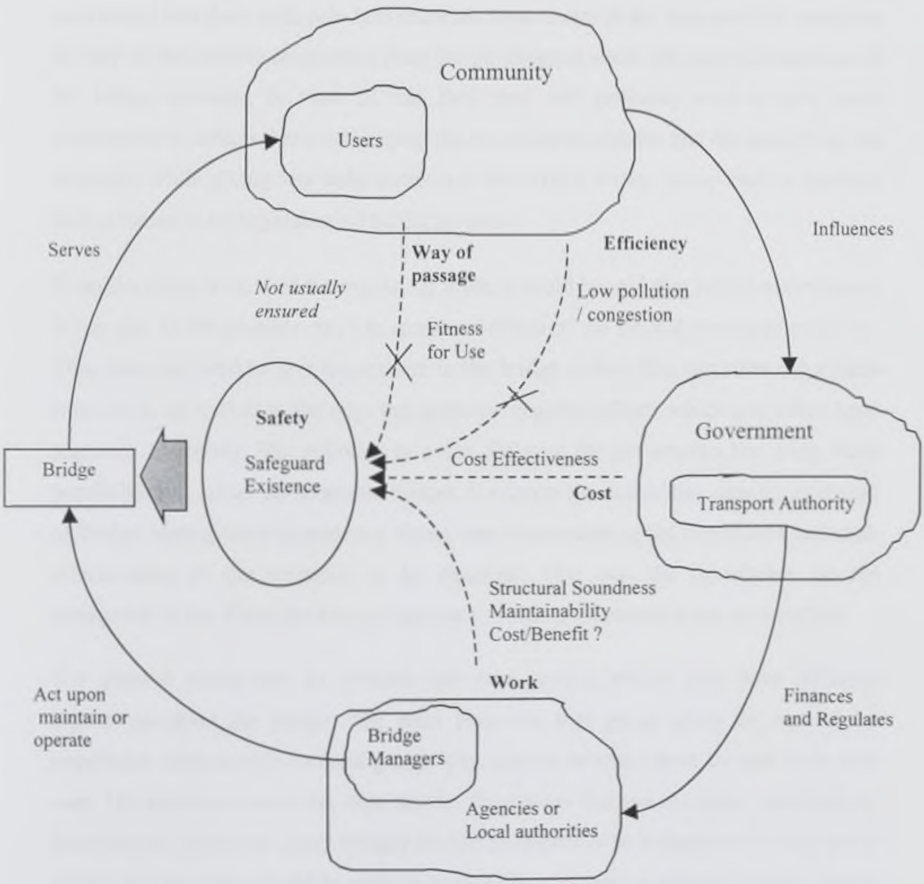

Figure 4.3 - A soft systems view of Bridge Management

For the purpose of discussing the diagram, the local authorities (in special the bridge managers or bridge engineers) will be designated as the *active actors*. They will be considered as directly responsible for the day-to-day management of the bridge stock.

The community, including the users, will be designated as the *passive actors*, because they suffer the effects of bridge deterioration or inadequacy but do not have any direct say in the maintenance of the structures. Finally, the government will be the *regulating actor*, being responsible for assessing and interpreting the needs expressed, directly or indirectly, by the passive actors and, at least in theory, transmitting them as directives to the active actor, while providing the necessary resources to their achievement.

The active actors usually see the set of bridges as a collection of assets and normally understand that their main role is to maintain these assets in the best possible condition so they do not receive complaints from the government about the poor performance of the bridge network. In view of this fact, they will probably tend to give more importance to defects that could impact the structural soundness and the stability of the structure, while giving less consideration to the effects on the transportation function unless forced to by legislation of public pressure.

From the point of view of the regulating actor, it could be said that bridge maintenance is just one of the possible ways to spend a fraction of the limited resources available. This actor will tend to give importance to the bridge defects that can raise complaints from users, as well as to the ones that generate negative effects which can affect large segments of society, like pollution or noise. Because the government has many other possibilities to spend the available budget, it expects the authorities directly in charge of Bridge Management to present a strong case demonstrating the importance and cost-effectiveness of the activities to be financed. This was the foundation for the emergence of the Value for Money approach, which is discussed in the next section.

The passive actors can be divided into two groups, which may have different aspirations about the bridge. The users form the first group while the rest of the population composes the second group. The concept of users must be seen here with care. The common use of the term implies the drivers that use the route supported by the structure. However, many bridges are just as important to pedestrians as they are to drivers and an effort should be made to ensure that they have a safe and reliable access to these facilities. Drivers that use nearby routes affected by the occasional unavailability of the structure might be considered as secondary beneficiaries of its existence. In general, users tend to see a bridge just as an "unseen" facility that provides a service assumed as guaranteed and that is just valued when not fit for purpose. Their main aim is to have the structure operational and the congestion low. The reduction in the level of service caused by the eventual lack of maintenance normally instigates the members of this group, especially drivers, to apply a considerable pressure on the government. The population in general also values the presence of the bridge and generally wants to ensure its safety. But in their view this must be balanced against the costs. The community is usually willing to contribute towards the improvement of traffic systems but resent high taxes and deplore the environmental impacts of transport, such as atmospheric pollution and noise.

Having understood the individual motivations of each actor, it is important to discuss how they interrelate and influence the process of Bridge Management. Initially, BM was driven mainly by the objectives of the active actor and was consequently focused on structural soundness and safety. The first important change to this panorama came when the cost objectives associated with the regulating actor began to gain prominence. In the U.S., the majority of the Departments of Transportation have already shifted their aims from just preventing bridge failures towards providing a more cost-effective management of the bridge system, as described by Turner and Richardson [1993]. This can be seen as a reflex of the growing pressure, not just in the U.S. but world-wide, to limit and justify the amounts spent on maintenance. The aims of the users have also progressively been incorporated in the formal procedures of Bridge Management. More than just considering cost effective solutions, the decision-making process have also begun to include the need of maintaining a certain quality of service. The concept of level of service has been introduced to express this need and is starting to be used in various Bridge Management Systems, as discussed in chapter 2.

There is today an increasing tendency to pay attention to another factor: the environmental consequences of transport. As seen earlier, for the population in general this is a major issue and even users are becoming more aware of the negative effects of traffic. According to a survey carried out by the Royal Automobile Club [RAC, 1997], the higher priority for users today would be cleaner air. In view of this changing perception there is growing stimulus for the adoption of a more sophisticated evaluation procedure to analyse the suitability of the provision of infrastructure considering the environmental aspects [ICE, 1996a]. For drivers, however, the desire to reduce environmental impact and achieve sustainability is balanced by the wish not to abandon their cars. Their view is biased by the fact that they receive a direct benefit from the use of the car. The distrust in public transport and the loss in comfort and independence make any change very difficult.

The government in the UK is starting to recognise the need to address other issues apart from cost and safety [Highways Agency, 1997]. In a recent consultation paper [DTER, 1998], it assumed the commitment of facilitating the mobility of people in an economically and environmentally sustainable framework. It also recognised the importance of taking into account local and global environmental problems like poor air quality, climate change, and increasing pressure on our natural and built environment. It defended the idea that these needs could be addressed by developing an effective and integrated transport policy at national, regional and local level [DTER, 1997b]. This is a stance that will probably be followed by other nations and is already affecting Bridge Management practices.

The recognition of the importance of considering these emerging views have instigated the idea of adopting more comprehensive criteria for decision-making, as discussed below, and influenced the proposals for the development of an advanced system, which will be discussed from chapter 6 onwards.

4.6 The Emergence of a Holistic View of Decision-Making in BM

The panorama discussed in the previous item justifies why the definition of Bridge Management aims is not an easy task. The commonality of interests in some cases is impossible because of a conflict is normally registered between the repair activities and the free flow of traffic and the desires of the various parties involved tend to diverge. Despite the difficulties decisions must be taken and structured criteria are necessary to ensure that they are consistent. The criteria used should not be based just on technical requirements but also include the series of other, less structured factors, that are taken into consideration by the decision-makers to fine tune and complement the technical solutions, as suggested by White et al. [1998]. In the case of bridges the usual requirements might include not just ensuring the structural safety and preserving the performance of the structure, but also reducing the level of inconvenience suffered by users and making economic sense.

In some situations, less common requirements might also apply, such as preserving historic structures, making sure that military routes are maintained open and satisfying political promises, between others. The relative importance given to each of these requirements can vary depending on the current state of affairs. While some of these requirements are of a more technical nature and can be seen as fairly stable, others are linked to society's perceptions and economic and political circumstances and are more prone to suffer sudden changes, affecting the final decision.

Decision-making exercises in Bridge Management can ultimately be seen as a reflection of the policies and the legislation being enforced at the time and therefore are susceptible to be influenced by changing cultural, social and environmental factors. This helps to explain why a new decision criterion based on the concept of value, which is a comprehensive and subjective quantity, has evolved in the last decade, as described below.

4.6.1 Value for Money Policy

One of the most important aspects affecting Bridge Maintenance operations today is the limitation of monetary resources available. A common trend towards the reduction of money available to public investment has been observed in the majority of countries in the past decades, due to the downsizing of governments and the increase in the demand for services. This panorama has directly affected the size of the budgets available for managing infrastructure elements. Haas [1993] cites a study showing that the total government spending on infrastructure in the U.S. has dropped sharply from 4.5% in the middle 60's to around 0.8% per year in the 80's. Similar situations are found in other countries, where authorities and agencies in charge of infrastructure maintenance and renewal are increasingly being stimulated towards controlling expenditure and developing methods to determine how to spend their restricted budgets wisely.

In a financial scenario where monetary resources are increasingly scarce it becomes ever more important to demonstrate in a clear cut way the usefulness of assigning money to bridge conservation in face of many competing demands from other governmental activities. The needs of the bridge stock must be examined inside a larger social sphere, suffering comparison with various other alternatives for public investment. As pointed out by Das [1996e], bridge engineers are increasingly pressed to justify the funding sought for maintaining bridges. Unfortunately, because of the negative attitude sometimes taken in relation to maintenance, the importance of the issue is frequently underestimated. Pressure from users can sometimes reverse this trend. The UK Government recently promised to expend more in road maintenance partially to offset the pressure caused by the continuos cuts in the construction of new roads [Warden, 1998]. Nonetheless, if public pressure from dissatisfied users helps to push the maintenance needs of some of the more busy and important structures, it is much more difficult to obtain money to preserve and repair bridges in minor or less strategic roads. In the later case, it will be necessary to present a very robust calculation showing the benefit of the proposed actions. The Value for Money (VFM) approach is seen as a fundamental instrument to provide a rational basis for justifying maintenance and improvement claims and is establishing itself as the dominant policy requirement regarding the evaluation of public investments.

Value for Money consists in determining the investment options that will bring the best return for the money invested [Dell'Isola, 1991] and has already been adopted as the standing policy in many areas of public administration, specially roads, as expressed by Bolton [1996] and Vassie [1997a]. The UK Government in particular has put a lot of emphasis in this approach and has recently instructed civil servants to examine "options for the delivery of the policy framework that minimise public expenditure cost and maximise the positive impact on the economy" [Milne, 1997]. According to the ICE [1996b], the Private Finance Initiative (PFI) has been conceptually designed to target value and the "Constructing the Team" report [Latham, 1994] have started to create an environment to deliver such value. The Highways Agency has followed the lead of the government and is strongly advocating the use of VFM to analyse Bridge Management strategies, as emphasised by Haynes [1997] and registered by Das [1997e]. Private consultants have already started to consider schemes based on this assumption, as seen in Constable [1997]. One important change brought by this stance is that the benefits of intervention considered in the analysis are not limited to the reduction of expenditure. The Value for Money approach supersedes the idea of awarding contracts to the lower bidders and establishes the principle that the measure of success of a project is the perceived value achieved [ICE,1996b].

The dissemination of the Value for Money policy is forcing the professionals responsible for bridge and road maintenance to develop sound ways of valuing their needs in order to justify their expenditure. When the concept is applied to the area of public investment, it becomes necessary to examine all the possible outcomes of every course of action under consideration and determine the best balance between expenditure and the added social value of the outcome. In other words, it is necessary to determine how to maximise the "value" to be achieved with the budget available.

4.7 CONSIDERATIONS ABOUT THE VALUE OF AN MRI STRATEGY

If Value for Money is accepted as the standing policy, the basic question becomes how to determine what composes the value of a MRI operation. In the process of managing bridges, decision-makers must try to simultaneously attend to various requirements. The value of a MRI operation would therefore depend on how much the consequences of that specific course of action would satisfy the set of requirements adopted by the authority in charge. Each possible courses of action to correct or minimise a bridge problem have a positive effect because it solves some structural or functional deficiency, improving performance. Interventions however customarily have also a negative effect associated with them, because they impact the Transportation Function of the structure and have therefore a deleterious impact on the traffic flow [OECD, 1981], as discussed before. The balance between these impacts will indicate the "value" of the MRI strategy.

The ICE [1996b] discusses various techniques of value management and argues that Value for Money should be a prerequisite of all commercial transactions. The problem however, is that the "economic value adding" exercises [White et al., 1998] used in private enterprises are based only in the increase of the value for shareholders or consumers. The concept of VFM in public decision-making must be more far-reaching. The objective must be to increase the social value of the structure. Following the idea that the main role of government is to promote increases in public welfare, it is logical to expect that the available money will be directed towards the bridges whose conservation or improvement would bring the most benefit to the community. The idea of value can therefore be linked to the notion of Bridge Utility. The question then becomes how to define the utility of a bridge. A specific model to express the Bridge Utility will be proposed in chapter 9 and is described in detail in Appendix II. Before that however it is considered adequate to make some considerations about the topic, as follows.

4.7.1 The Concept of Bridge Utility

Bridge utility is a complex concept to define. The examination of the classification criteria used by some authorities to define the priority of bridge activities can help shed some light on the factors that must constitute the Bridge Utility. The Sufficiency Rating Criteria [FHWA, 1988] considers the structural adequacy, the user safety, the serviceability, the functional obsolencece and the essentiality for public use. The Indiana BMS [Woods, 1993] meanwhile is based on the consideration of structural safety, traffic safety, community impact and investment effectiveness. As suggested by these examples, the importance given to a bridge is usually dependent on a combination of the several factors discussed in 4.3. Structural soundness is considered paramount but functional performance is gaining importance because it is being recognised that the main role of bridges is to allow the efficient movement of people and goods over difficult spots, as discussed in chapter 2.

The traditional requirements do not consider the fact that sometimes importance might be attributed to bridges for other less objective reasons, such as emotional considerations. Burks [1995] reports a case where a completely obsolete footbridge was earmarked for demolition but the public reaction to the announcement was so intense because of the sentimental attachment of the local community to the structure that it prompted the authority to change its plans and carry out the rehabilitation of the structure. It would be necessary to consider these less structured factors to have a reliable appraisal of the real social utility of a certain bridge structure. Having in mind these considerations, Bridge Utility will be defined in this thesis as expressing the social importance given to a certain structure that is offering a certain level of service and has a certain history and particular characteristics.

One of the most important components of Bridge Utility will be the actual value attributed by the various parties of society to the structure. Various dimensions to the Bridge Value could be identified. First, there is the pure financial value of the asset, expressed by the amount of materials, time and work used in its construction. It is necessary to protect and safeguard this considerable investment and make sure that there is an adequate return for the investment made. Additionally, there is the functional value of the bridge, which depends on the number of users and the importance of their trips. There is also the Human Value, expressed by the potential cost in lives due to accidents generated by substandard conditions in the bridge or in the case of collapse of the bridge because of excessive deterioration of its parts. As discussed above, some special characteristics can also raise the value of a specific bridge, such as aesthetic or historic considerations. Finally, political and legal circumstances could influence the importance given to certain structures.

Apart from the value of the bridge, the utility will have other components related to the effect of the structure on users and society. The saving of time that would be wasted using an alternative route is an example of the utility offered by the bridge caused to a user. As pointed by Tilly [1997], traffic delays can cost as much as ten times more than the maintenance work. The DOT in the UK shows in an exercise [BA 28, 1992] that the whole life maintenance costs of a concrete bridge of 323 m2 of deck area can rise to £1,163 for repairs, £2,490 for traffic management and £398,560 for traffic delays. This example clearly shows the need to investigate how these costs can be assessed and the criticality of including them in a structured way as part of the decision-making criterion. The reduction of noise and atmospheric emissions associated with the traffic congestion that arises from the reduction in performance or loss of a bridge means that it is necessary to add an environmental component of the bridge utility. The consideration of environmental factors is becoming especially important because there is a growing tendency towards developing policies characterised by sustainability and acceptability, as discussed by the ICE [1996a]. The FHWA [1998] is currently undertaken feasibility studies to incorporate environmental considerations in the appraisal mechanisms for funding in the U.S.

The development of a theoretical framework based on the concepts of Value and Utility will be fundamental in the proposal for an improved appraisal model discussed in chapter 9. The suggested way to express the various utility components will be by establishing a utility function, as discussed below.

4.7.2 The Use of Utility Functions to Express Bridge Value

As seen above, the value of a MRI intervention is closely associated with the notion of bridge utility, which in turn is composed by several elements. It may be assumed that a different importance would be given to each one of these value elements. The relative weight given to each will depend on the underlying system of values of the authority in charge of Bridge Management. This system of values is ultimately a reflection of the vision of public priorities held by the government and, as such, it is dynamic and might vary over time. Special circumstances can also sometimes significantly alter the existing system of values by swaying public opinion and creating more favourable conditions to push for MRI operations. For example, the 1994 earthquake in Northridge and the following one in Kobe in 1995 raised public sensitivity to seismic retrofitting enough to allow authorities in California to take advantage of the situation and pass a proposition committing £1.3bn to bridge repair and improvement [Greeman, 1996]. New legislation or changes in traffic pattern can render the current maintenance policies obsolete and force the adoption of new aims and objectives. All these effects must be taken in consideration during the decision-making analysis and provisions to include them in some form in the decision models used in computer algorithms must be made. One possible way to express them is by using a utility function.

The decision-making according to a Value for Money approach could be made by employing a subjective multi-attribute utility function to represent the effects of repairing a certain bridge structure, following the line of work described by Ng [1996]. Jones-Lee [1994] denominates this approach as Decision Analysis and emphasises that it is not aimed at "turning decision-making into a formulaic mechanical procedure" but to "facilitate decisions concerning complex issues by providing the decision-maker with an ordered structure within which to assemble and analyse a wide diversity of information". Utility functions are commonly used in classical economy theory as an expression of a consumption vector of a private customer [MVA Consultancy, 1994] that derives utility from the consumption of commodities. The consumer will try to maximise the function subjected to his available resources. A similar treatment could be proposed to represent the individual utility of each bridge, as follows:

$$U(x_i) = UC_1(x_i) + \ldots + UC_i(x_i) + \ldots + UC_n(x_i) = \Sigma_n [UC(x_i)] \qquad \text{(Eq. 4.1)}$$

Where $U(x_i)$ is the utility function of bridge x_i and $VC_n(x_i)$ are the various utility characteristics of the bridge x_i. What is however important is the variation in utility resulting from the adoption of a certain MRI strategy, which could be represented by:

$$U(x, MS_k) = \Delta V(x,a_1)\, \delta 1_k + \ldots + \Delta V(x, a_i)\, \delta i_k + \ldots + \Delta V(x, a_n)\, \delta n_k \qquad \text{(Eq. 4.2)}$$

Where $U(x, MS_k)$ is the utility of MRI strategy k in bridge x, $\Delta V(a_i)$ is the variation in bridge value caused by the adoption of course of action a_i, n are the number of different courses of action considered and δi_k is a dummy variable that represents the adoption or not of the course of action a_i in the strategy k.

It would be possible to give different importance to these characteristics using a system of relative weights, as in equation 4.3. This is the type of utility function that will be used in this thesis to express the various components of Bridge Utility.

$$\Delta V(x, a_1) = \alpha_1 VC_1(x, a_1) + \ldots + \alpha_i VC_i(x, a_1) + \ldots + \alpha_n VC_n(x, a_1) \quad \text{(Eq. 4.3)}$$

Despite the difficulties, the author believes that the use of utility functions can help develop a more adequate model for decision-making in Bridge Management, as will be described in greater detail in chapter 9. However, the use of this approach is dependent on establishing the value characteristics of each bridge. It is necessary to bring the various requirements to the same dimension, a complex exercise. Traditionally the most adequate basis to translate the various components of value would be the monetary cost, as discussed in the next section.

4.7.3 Expressing Value in Monetary Terms

The Value of a MRI option was defined as being largely a result of the variation in utility of a Bridge. The Bridges Utility is in turn expected to be a combination of various components expressing the various dimension of bridge value. This can be expressed in different units. It is necessary to find a way to combine them to have an adequate representation of the MRI value. The question is to determine to which dimension should all the components of be reduced.

Some attempts have been made to base decision-making in a structural safety criterion. Due to the inherent unwillingness of all parties involved in letting bridges collapse, this undoubtedly seems an attractive solution. However, the safety criterion is considered too narrow to contemplate the universe of decisions related to the determination of the most adequate MRI strategy.

Decision-making criteria based on functional factors have also emerged. In these cases, the use of some kind of user satisfaction index is usually advocated. Mohseni et al [1993] report that in Illinois the performance of the Pavement Network is evaluated by measuring the percentage of vehicle-miles travelled on good pavement over the total VMT (vehicle-miles travelled), with good pavement being defined according to a local rating system. This kind of approach is however also limited in scope and is open to criticism because of the subjective nature of the indexes used.

The most adequate solution to the problem seems to be to convert all factors to a monetary basis. The utility components could then be compared taking cost as the common denominator, which, as pointed out by Andersen and Lauridsen [1993], is the only sensible way to do that. To do this, they emphasise that it is necessary to assess the representative cost of each factor that influences the decision. For example, the results of a bridge collapse or the impact of a low level of service should be estimated and expressed in a monetary basis. This might seen a difficult task but according to White et al [1998], many of the factors involved in a decision that may at first seem non-economic can be expressed in monetary values.

The confirmation that cost is the most natural common denominator to be used for decision-making can be found in Turner and Richardson [1993], who argue that Bridge Management practice is ultimately driven by cost considerations. Having concluded that cost is the basic dimension to which all value characteristics should be reduced to, it is easier to understand why Economic Analysis has become the core of strategy appraisal in the decision-making process of contemporary BM practice. This will be the topic of interest of chapter 5.

4.8 SUMMARY

This chapter discussed the decision-making process in Bridge Management. A soft diagram was used to model the relationships between the various parties involved and the bridge structures and it was concluded that it is necessary to extend the decision criteria to consider the external costs of MRI actions, especially the environmental impact. The need for a more comprehensive appraisal that includes the subjective factors that influence decision was used to justify the emergence of the Value for Money policy in recent years. The chapter also investigated how the Value of a MRI strategy could be expressed using a utility functions and argued that the most suitable way to extract a common figure from the function that could be used to prioritise actions would be to reduce all the utility components to a monetary basis. Chapter 5 will explore which economic analysis could be used to support the economic appraisal necessary to subsidise the decision-making process.

Chapter 5

Economic Appraisal of MRI Strategies in Bridge Management

5.1 Introduction

This chapter will discuss how Economic Analysis techniques can be used to support the appraisal activity in Bridge Management. Based on the examination of the existing literature on the topic, it is argued that incremental benefit-cost ratios are the best indicator of the adequacy of a certain MRI strategy. A brief review of the principles of Cost Benefit Analysis (CBA) is therefore undertaken. The importance of considering in public investment appraisal exercise all the social and environmental components of the problem is emphasised and the decision of adopting a social version of CBA justified in these terms.

Since CBA is based on the consideration of the monetary value of the positive and negative impacts of each alternative course of action, a discussion about the valuation of impacts is carried out, giving emphasis to the techniques for estimating the monetary value of non-monetary impacts. The utility of these techniques is demonstrated by the analysis of MRI impacts, which shows that the majority of external impacts are of a non-monetary nature. The chapter finalises with a discussion about the necessity of including the external impacts in the analysis to produce a reliable appraisal tool.

5.2 Techniques for Economic Appraisal of MRI Strategies

Several techniques could be used to undertake the Economic Appraisal necessary to subsidise the selection and prioritisation of MRI actions. The choice of the best one to adopt will ultimately be based on the objectives of the decision-maker. In some cases, the objective could be to determine the combination of actions that would minimise the public expenditure in the short or long term, without considering the amount of benefits accrued or assuming that all alternatives would produce similar outputs. In these cases, a cost minimisation technique [Brent, 1996] could be used. This approach is sometimes adopted in Bridge Management to determine the minimum level of investment necessary to maintain the condition of the network.

Another possibility would be to find the actions that would bring the most benefits, no matter the cost. If the benefits considered in this case were just the ones related to the improvement of the condition of the bridge, this strategy would be reduced to a "do worst first". This scenario can be understood as if the bridge utility function was limited to include just the structural soundness or other similar parameter that would indicate the structural performance or the risk of collapse of the asset. However, this would imply a very narrow interpretation of value and goes against the recommendations on the ICE report on value management [ICE, 1996b], which suggests that the scope of the value characteristics considered should be as broad as possible. The problem with both the "cost minimisation" and the "worst first" strategies is that they do not establish a relationship between the expenditure and the expected return in terms of beneficial impacts. Consequently, they are not efficient in asserting the achievement of Value for Money nor are adequate to take into consideration the variations in Public Welfare. To do that, it is necessary to compare costs and benefits and determine if the budget is being spent in the wisest way.

There are various ways to compare cost and benefits, depending on how the benefits are measured. According to Brent [1996], when the consequence is the same but the cost varies in magnitude between alternatives Cost Effectiveness Analysis (CEA) can be used. If the project effects are expressed using a subjective value function, a Cost-Utility Analysis (CUA) is more adequate. The problem is that these two alternatives can just assess the effectiveness of the expenditure but are not able to assess the social relevance of the project. If the social worthiness of the project must be assessed, it is necessary to compare benefit and costs in the same basis.

The most common reference in this case, as highlighted in chapter 4, is the monetary one. When cost and benefits are compared in monetary terms, the analysis is reduced to a Cost-Benefit Analysis (CBA). Brent [1996] emphasises that, in strict terms, the term CBA would be designating an analysis referring to any private entity. In such an approach, the costs and benefits considered would be the private ones for that individual enterprise and would include just the factors that could be measured in financial terms. However, in public decision-making it is necessary to consider the question from a wider point of view, trying to include all possible effects, as suggested by White et al. [1998]. This means that, in the case of Bridge Maintenance provision, it would not be enough to make a pure financial appraisal from the point of view of the maintenance agency, but that it would also be necessary to consider the impacts on users, the environment and society.

According to Thompson [1995], the social version of the traditional CBA is the best method to be used when there are overall social objectives being pursued and the problem transcends purely financial considerations. The Social Cost-Benefit Analysis (from now on just CBA, as used in the literature) has the same structure of a private CBA but considers the needs of society as a whole [Pearce & Nash, 1981], replacing private costs and benefits with social costs and benefits [Brent 1996]. "Social" CBA is one of the most widely used techniques for the financial appraisal of public projects [Brent, 1996]. Thompson [1995] argues that it provides a logical framework to evaluate alternative courses of action when a number of factors are highly conjectural in nature, like in the case of Bridge Maintenance.

In the UK, CBA has long been applied to the domain of transportation, starting with the evaluation of the M1 motorway project in 1960 [Hanley & Spash, 1993]. Since then it has been routinely recommended by the Department of Transport for the evaluation of investments in transport. In the early 1970s a formal procedure to evaluate trunk roads schemes using the technique, denominated COBA [DOT, 1981][COBA, 1996], was introduced. The trend towards using CBA in public decision-making is reinforced in guidance notes from the Treasury [HM Treasury, 1998]. All these facts support the suggestion that CBA should be preferred technique for appraising MRI actions.

5.3 Principles of Cost-benefit Analysis

The origins of CBA are firmly associated with the evaluation of Public projects. The method is adequate for this use because it is based on the Principles of Welfare Economics [Brent, 1996]. This means that, in theory, the Pareto criterion of welfare improvement would have to be used to check if a project were going to be supported. The traditional interpretation of this criterion defines that only if no individual suffered any loss and some individuals were benefited a project would be acceptable. This is considered a very restrictive requirement [Pearce & Nash, 1981] and CBA evolved to use the principle of potential compensation with the adoption of the Kaldor-Hicks test [Freeman, 1986]. This means that a policy will be judged beneficial if there is a net benefit for society, i.e., if gainers are able to secure enough benefits to potentially compensate the losers and still have some net gain [Pearce & Nash, 1981]. A real transference of the gains rarely takes place in reality, but the criterion of net gain has become the main standpoint of the method.

5.3.1 Generic Structure

Figure 5.1 contains a representation of the basic structure of a typical CBA analysis. Whilst there might be some objections to how the stages are defined, the structure suggested provides a guide to the essential steps that would compose the analysis.

As seen in the figure, the first step is the establishment of the various investment alternatives. It is then necessary to identify impacts. The monetary impacts form the cost. Positive non-monetary effects are usually called benefits while negative non-monetary effects are sometimes denominated as disbenefits. A monetary basis is used to compare the various impacts. White et al [1998] highlight that it is many times difficult to attribute monetary values to certain benefits and disbenefits, but that this should be tried as much as possible. Thompson [1995] reinforces this point and argues that the economic relevance of each impact must be determined and quantified. If market values cannot be used it will be necessary to value impacts using shadow values or some kind of indirect valuation approach, as discussed in 5.4.

According to Prest and Turvey [1968] (cited by Brent [1996]) it is necessary to take "a long view" (looking at repercussions in the further, as well as the nearer, future) as well as "a wide view" (allowing for side effects of all kinds on all parts involved) of the impacts. Because of this need to consider impacts in the future and the usual large duration of public projects, discounting is an important step if it is assumed that money has a time–dependent value. This is a fair assumption because according to White et al. [1998], people have a preference for accepting money now than in the future. This is a mainly a reflection of the fact that interest can be earned on the money if it is available now but it also expresses other factors, like the possibility that the person may not live to experience the future benefits [Brent, 1996].

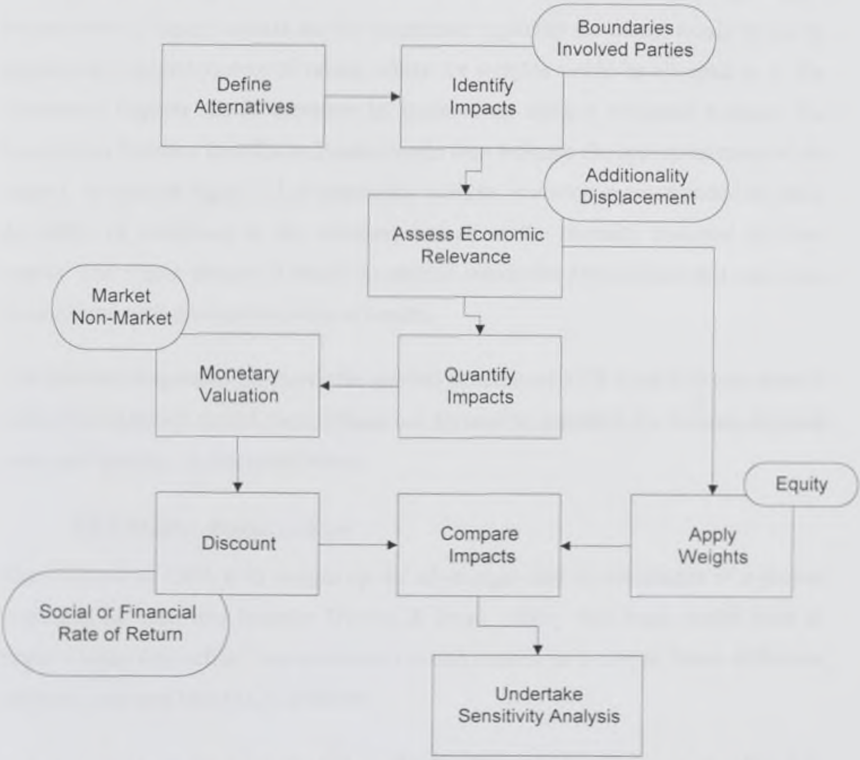

Figure 5.1 – Basic structure of a CBA. (Adapted from Hanley and Spash, 1993).

In the case of public investment appraisals, there is a lot of discussion about which rate of interest should be used to represent the social attractiveness of capital. The author believes that in the case of Bridge Management, the rate of interest for internal borrowing by the government, usually expressed in treasury bonds (or gilds, in the UK) should be used, since that would be the interest paid by the government if it was necessary to borrow the money to undertake the MRI programme.

Having discounted the values, weights could be applied to represent the differences in the importance attributed to each impact or to explicit equity considerations, as discussed by Brent [1996]. Some authors defend the idea that CBA should be restricted to allocational efficiency and not make equity considerations. The author of this thesis disagrees and believes that the use of weights is fundamental to allow an adequate expression of the system of values held by the policy makers. The author concurs with Brent [1996], who argues that in fact there is no possibility of avoiding using weights, because even if equity aspects are not considered explicitly the model would in fact be expressing a neutral system of values, where the weights would be all equal to 1. The discounted impacts should therefore be summed up using a weighted average. The comparison between benefits and costs would then indicate the appropriateness of the project. As seen in figure 5.1, a sensitivity analysis is always recommended to check the effect of variations in the monetary values or the intensity assumed for each impact. The whole process is based on various subjective assumptions and care must be exercised with the interpretation of results.

The previous discussion illustrated the general structure of a CBA but it is important to notice that different model formulations can be used to establish the balance between costs and benefits, as discussed below.

5.3.2 Model Formulation

The principle of CBA is to weight up the advantages and disadvantages of a project expressed as costs and benefits [Pearce & Nash, 1981]. The basic model used to express value (or welfare improvements) would consist in a simple linear difference between costs and benefits, as follows:

$$V = B - C \qquad \text{(Eq. 5.1)}$$

A simplified notation is adopted where B represents the total benefit (the sum of all benefits) and C the total cost (the sum of all costs). Brent [1998] defines this difference as the economic efficiency of a project. The model is consistent with the idea of net utility exposed by Hanley and Spash [1993], which is represented by the total utility less the cost and establishes a connection between CBA and the utility functions used to express bridge value discussed in chapter 4. The concept could be extended to establish the utility of a certain maintenance strategy, as follows:

$$U_{net}(MS_y) = \Sigma_x [U(x)] - \Sigma_x [C(a_{(k,x)})] \qquad \text{(Eq.5.2)}$$

Where U(x) is the utility of an bridge x given the adoption of an course of action k, U_{net} is the net utility of the bridge stock given maintenance strategy MS_y and C are the total costs of this strategy, composed by the sum of the costs of the course of actions $a_{(k,x)}$ for each bridge x.

Because of the need to consider the effects of time on the value of money, as discussed in the previous item, the monetary values of the various impacts of a project are usually discounted to a common time reference. This reference is usually the present day, which leads to the well-known concept of Net Present Value [Brent, 1996; Mackie, 1998a]:

$$NPV = B_{adj} - C_{adj} \qquad \text{(Eq. 5.3)}$$

Where B_{adj} are the discounted benefits expressed by:

$$B_{adj} = \Sigma_i[B(i)/(1+r^{n(i)})] \qquad \text{(Eq. 5.4)}$$

With B(i) representing the i-th impact, r being the discounting rate used and n(i) the number of discounting periods between the occurrence of the impact i and the date taken as the basis for calculating the NPV. A similar formulation would be used for the discounted costs.

In principle, a project with a negative NPV would not be undertaken. This might be altered, however, when benefits or costs are valued differently because they have a special nature or are incurred by certain members of society that the decision-make wants to treat in a different way. Distribution weights might then be used to express the fact that these aspects are being considered:

$$NPV = \Sigma_i [\phi_i B_{adj}(i)] - \Sigma_j [\omega_j C(j)] \qquad \text{(Eq. 5.5)}$$

Where ϕ_i are a series of weights expressing the underlying system of values that gives more importance to some benefits over others and ω_j is the relative importance given to the various costs, usually linked to equity aspects, as discussed in the previous item. More complex model formulations are discussed in Brent [1996], with the inclusion of terms to represent the social cost of obtaining public funds, for example. The exploration of these models is not considered as necessary for the discussions that will be conducted in this thesis.

The NPV model is adequate to determine if a project would increase or decrease social welfare, being therefore a good indicator to decide if the project should be undertaken if money was available. The NPV model can also be used to chose between projects. The basic acceptance rule would be that a course of action Z is chosen if the net benefits exceed those of the next best alternative. Layard and Glaister [1994] argue that this procedure will lead to the choice that brings the highest benefits, giving the constraints in place. However, Pearce and Nash [1981] argue that it would be more adequate to measure up costs and benefits by establishing the ratio between the two. The cost-benefit ratio is frequently defended as a better indicator of the efficiency of a project. Mackie [1998a] discusses this point and concludes that NPV can impart a size bias when ranking projects. He also discards the use of the Internal Rate of return, arguing that this is difficult to calculate and gives a "misleading weight to benefits accrued in the first year". He recommends the use of the ratio NPV/Cost. Using the LaGrangean form he establishes a criteria that a project would be undertaken if its benefit-cost ratio exceeds λ, the shadow price of capital. This thesis will adopt a similar approach. The basic model to be used in this work therefore will be:

$$V = \{\Sigma_i [\phi_i B_{adj}(i)] - \Sigma_j [\omega_j C(j)]\} / \Sigma_j [\omega_j C(j)] \qquad \text{(Eq. 5.6)}$$

With both cost and benefits being discounted to the same point in time, a system of weights being applied to express different social valuations of the impacts and disbenefits considered as negative benefits. All projects with $V > 0$ will be considered for ranking.

5.3.3 Simplifications and Limitations

As explained by Brent [1996], the theory of cost-benefit was founded on the notion of a rational individual making decisions in a free market situation. Theoretically, when CBA is used to assess decisions affecting large number of individuals, it would be necessary to assess the costs and benefits affecting each individual. The final cost-benefit ratio would be the result of the aggregation of all these individual values. In practice, however, the examination of the preferences of each individual is unfeasible in the great majority of situations. According to Hanley and Spash [1993], when valuations of the opinions of individuals are not available, they can be replaced by values sought directly from the decision-maker. Pearce and Nash [1981] discuss the problems involved in assuming the set of values of the decision-maker as representative of those of society but conclude that sometimes this is the only feasible option. If the same system of values is used consistently to appraise all projects, Brent [1996] considers that there is no necessary bias in using CBA. He argues that the use of an explicit value function can even prevent the manipulation of decisions to favour projects preferred by the decision-maker.

Hanley and Spash [1993] discuss some other controversial issues that still surround CBA. They examine some questions related to market and consumer behaviour in practice and pay special attention to the discussion about the necessity of considering equity alongside allocation efficiency as the basis for assessing changes in welfare. Despite these considerations, they consider that the CBA technique provides an input to decision-making that has no substitute at present. The main problem for the use of CBA as an effective economic appraisal tool however is considered to be the difficulty in assessing monetary values to the various impacts of deterioration and maintenance.

5.4 The Monetary Assessment of Impacts

As discussed in chapter 4, the merit of a MRI programme is increasingly being assessed in terms of its adherence to a Value for Money policy. The previous section defined that the value of a MRI strategy can be expressed by the potential cost-benefit ratio. The monetary valuation of the impacts of MRI actions is therefore an essential activity. It is necessary to develop adequate ways to assess costs and benefits and establish sound procedures to provide values for them in order to carry out a reliable analysis. There are various ways to do that, as follows.

5.4.1 Market and Shadow Prices

Many of the impacts of a project alternative have a sound economic basis. People pay for services and goods and the economics of supply and demand in a free market define and regulate the prices. In these circumstances, the market prices can be assumed as representing the social cost of the good. This transformation of prices in costs assumes the validity of a certain willingness to pay (WTP) relationship and is an indirect expression of the underlying system of values prevalent and which guides individual actions. Because the willingness to pay can change depending on the quantity consumed, it is necessary to use the marginal social cost, or the cost of producing one extra unit.

In many cases, the marginal social cost (or benefit) can be estimated directly from the market prices. However, there are cases when the market prices will not be a good indicator of these values. This occurs for example when there is imperfect competition that creates a monopoly, with prices maintained artificially high [Hanley and Spash, 1993]. Government intervention can also distort supply and demand curves. Finally, the cumulative WTP is higher than the current price level, as explained by Brent [1998]. There is therefore a consumer surplus that needs to be considered if the full social benefits of a project are to be measured.

When imperfections are detected, shadow prices are used to reflect the true scarcity and value of a resource. The shadow prices can be defined as the "increase in social welfare resulting from any marginal change in the availability of commodities or factors of production" [Brent, 1996] and correspond to the social opportunity costs of the resources used [Drèze and Stern, 1994]. According to Brent [1996], the most general method for determining shadow prices is using LaGrange multipliers. Given a utility function, an objective and a set of constraints, the level of prices that maximise the value function, as expressed by the multipliers, can be assumed as the shadow prices. While shadow pricing is a useful tool, in some extreme cases there might not even exist a market and the monetary value of the resources may have to be assessed by other means, as discussed below.

5.4.2 Valuation of Non-Monetary Impacts

According to Hanley and Spash [1993], it is common for a CBA to be faced with the need to take into consideration the value of a good not traded in markets and for which no obvious price exists. While some techniques have been developed to try to extract such values, sometimes the factors affecting a decision cannot be expressed in monetary terms. In this case they are often called intangibles or irreducibles [White et al, 1998]. Layard and Glaister [1994] argue that the use of CBA becomes impossible if the impacts cannot be properly valued in monetary terms. They suggest that, when faced with the existence of intangibles, it might be useful to compare the cost of providing the same beneficial outcome in different ways, without expressing this outcome in monetary terms. This procedure would imply a switch from CBA to cost-effectiveness analysis (CEA).

The problem is that it is difficult to provide the same outcome in Bridge Management. However, if a satisfaction index with a subjective and monetary expression is defined, it might be possible to use a CEA at a strategic level, looking at which portfolio of projects would bring similar changes to a total satisfaction index resulting from the summation of individual indexes. Nonetheless, because the outcome is not being measured in monetary terms, it is not easy to prove in an objective way that the operation makes financial sense, that is, that the benefits accrued are worth more the expenditure incurred. That is the reason why, despite the difficulties, various authors still defend the use of CBA. Several methodologies have been developed to try to attribute monetary values to these types of effects and have provided good results.

Hanley et al. [1997] divided the methods to value non-market items such as environmental goods in two categories: direct and indirect methods. In the direct methods the system of values of an individual is inferred by asking him to state his preferences in face of a particular choice that could cause different outcomes, usually associated with some environmental change. These are the so-called Stated Preference (SP) Methods, of which the most famous is the Contingent Valuation Method (CVM). In the CVM people are asked about their willingness to pay (WTP) for an increase in environmental quality or about their willingness to accept compensation (WTAC) to forgo such an increase. Structured interviews are usually used to collect people's preferences [Saelesminde, 1995]. According to Hanley et al. [1997], because a third party usually chooses the level of environmental quality, these measures correspond to the compensating surplus rather than to the equivalent or compensating variation, where the individual might choose a combination of quality and quantity for the resulting environment. Other stated preference methods that have emerged recently include Contingent Ranking [Lareau and Rae, 1987], Conjoint Analysis (CA) [Saelesminde, 1995] and Stated Preference Analysis [Hanley et al., 1997]. Hensher [1994] reports a shift from CVM to CA in the field of transportation analysis due to the fact that the direct questions about WTP posed by CVM questionnaires are more difficult to answer that the paired choices used in CA.

In the indirect methods, instead of measuring the preferences of the individual directly, these are inferred from their behaviour in related markets. These methods follow the suggestion of Layard and Glaister [1994] that the value of non-market items can be assessed from the money a consumer would pay for another good that he values equally. According to Hanley et al. [1997] the most common of revealed preference (RP) methods are the Travel Cost Method (TCM) and the Hedonic Pricing (HP) method. They also cite the dose-response and the averting expenditure/averted costs approaches that would correspond to the Production Function Methods referred to by Hanley and Nash [1993]. The latter have however received less attention and will not be discussed in this work.

The TCM uses the cost of consumption as a proxy for the value of non-market goods. This method is usually used to value outdoors or recreational sites. The consumption costs would typically include the travel costs, entry fees, on-site expenditure and any other outlay on capital equipment necessary for consumption [Hanley and Spash, 1993]. The HP method is derived from the theory of value proposed by Lancaster [1966] and seeks to identify the value of non-market goods by examining how a change in their quantity of quality would affect the price of a related marketed good. Hanley and Spash [1993] give the example of finding the relationship between certain levels of environmental services such as noise or particulate levels and the price of houses. Brent [1996] discusses the use of the method relating the various characteristics to a subjective satisfaction index instead of a marketed good. The main criticism to the use of HP and TCM is that they are not able to estimate non-use values, but some authors dispute this view, especially in relation to the TCM.

Mackie [1998b] present a comparison between values of time calculated using SP and RP modes and concludes that the overall degree if similarity of the results is "very reasonable". Like in this reference, there is not enough empirical evidence to suggest that SP methods are better than RP methods or vice-versa. The choice of technique is currently a matter of personal preference or schools of thinking. It is necessary however to have considerable care in the design of the experiments in both cases to avoid distorting the results.

5.5 Applying the Concept of CBA to the Analysis of Bridgeworks

The basis for an adequate Economic Analysis using the CBA technique is the determination of the various impacts deriving from each possible course of action. It is adequate therefore to discuss which impacts would normally constitute the costs and benefits of a MRI strategy.

5.5.1 MRI Costs

Each alternative MRI strategy has an associated Cost, which expresses the expenditure incurred by the bridge authority (sometimes also denominated Bridge Agency or simply Agency) to finance the intervention. This Cost could include various elements such as the cost of setting-up the site, the cost of actually performing the MRI operation and the traffic management costs. The author believes that there are serious limitations in the way that the Costs of MRI strategies are being estimated today in Bridge Management Systems. This topic will be discussed in detail in chapter 6. One of the main contributions of this thesis is a proposal for a more accurate structure to define and aggregate agency expenditure (see chapter 9).

5.5.2 MRI Benefits

The Benefits of a MRI intervention are normally represented by the offset of some of the negative effects caused by deterioration or obsolescence. Table 5.1 shows a summary of the deleterious consequences associated with the deterioration of a bridge (and the ensuing compromise of performance) classified according to their incidence.

Table 5.1– Examples of negative consequences of bridge deterioration.

Incidence	Examples
Internal Impacts on the Agency	Increase maintenance expenditure.
External Impacts on Users	Time loss, higher safety risk and increased vehicle operational costs.
External Impacts on the Environment	Higher emission of pollutant gases and increased levels of noise.
External Impacts on Society	Reduction in productivity due to loss of time, anxiety and exposure to noise; expenditure in care for the victims of accidents; increase in the cost of goods, etc.

As can be deduced from the data on the table, there might be certain positive impacts to the bridge agency resulting from the MRI intervention. These impacts would be associated with the avoidance of more expensive treatments in the future due to the adoption of preventative measures or the prompt response to corrective needs. As widely registered in the literature, the delay of maintenance actions tends to significantly increase the expenditure necessary to solve the problem. From a social point of view, however, the most important benefits would be the ones resulting from the reduction of the external effects of deterioration on users, the environment and society. As seen in the table, the consequences of deterioration usually have a negative effect on Public Welfare and their reduction would normally be considered as a socially adequate measure. One additional aspect to consider is that the undertaking of MRI operations can aggravate, if temporarily, some of the negative effects of bridge deterioration seen in table 5.1. As a result, a certain amount of disbenefits will occur and should be considered in the calculations.

5.6 External Impacts of MRI Strategies

The role of the Economic Appraisal is to assess all the impacts of MRI actions and find the strategy that will result in the greatest net benefit for the lower cost. To this end it is especially important to understand the external impacts. This item will discuss the nature and make some considerations about the valuation of these impacts.

5.6.1 Impacts on Users

The impacts on users, commonly known as User Costs, are mainly a consequence of the disruption of service due that occurs when deterioration affects the performance of the bridge or when MRI interventions are being carried out. The main types of impact on users are the increase in the Vehicle Operational Cost (VOC), the loss of time incurred because of delays and the potential risk of injury, death and material losses because of failures or accidents [Robinson, 1993]. The *Vehicle Operating Cost* can be defined as the expenditure incurred by a vehicle owner or user during its use. It includes consumables and the wear and tear of the mechanical parts but depreciation, licensing and garaging should not be considered because they are incurred irrespective of whether a particular journey is made [Thomas, 1972]. Road Haulage Associations or similar institutions can be useful sources of information for the value of the VOC, since they usually record and calculate the average cost of operation for heavy goods vehicles. Buses and rail companies can also be a good source of information, since they regularly appropriate these costs to calculate fares [Robinson, 1976]. Values for the VOC of private cars are published by driver's association or the government.

Another important impact on users is the *Time Loss* originating from delays and congestion. There are many difficulties associated with assessing this cost because the value of time will be dependent on the alternative use of time by the person affected. Also, the time losses are frequently small or almost negligible to individuals. Because of the large flows carried out by some structures, the total cost might be significant but some researchers argue that the use of the total aggregated value of delays would not represent the actual importance giving to the loss of a few seconds by each individual. Despite this warning that aggregation might overvalue the Time Loss the consideration of this impact is seen as essential because congestion is one of the main causes of complaints by users of the transportation system, as seen before. Additionally, in some cases, the cumulative time losses for each individual are well in excess of some seconds. A survey recently published [The Times, 1998] indicated that approximately one third of the journey times at peak hour in London was wasted in stops.

The last of the most significant impacts on users is the *increase in the risk of accidents*. The obsolescence or deterioration of structural elements accentuates the risk of collapse. Problems with non-structural elements such as the pavement, signalling elements or parapets can increase the chance of car accidents. Even when the deterioration is not considered structurally important it can present a hazard to pedestrians and passers-by, such as falling pieces of concrete. These circumstances can put in peril the life of users or might subject them to the risk of material losses. MRI operations will normally reduce these risks, generating a benefit. One important thing to highlight however is that there is always a residual degree of risk, even in a bridge in perfect condition. It is the monetary expression of the risk differential that really needs to be accrued.

Apart from these main impacts, some other less studied user impacts are also mentioned in the literature. Peacock [1985] discusses the fact that disruptions of service could have an adverse psychological effect on users. Due to the complexity of measuring these effects they will be considered as being outside of the scope of this work.

5.6.2 Impacts on Society

The external impacts on society, as seen in table 5.1, are normally difficult to assess and value because of their long ranging nature. These effects will therefore not be considered in this work. There are however some monetary costs that are incurred by individual members of society that are not users of the structure. People living in the neighbourhood of a roadway are exposed to considerable levels of noise and bridgeworks might increase these effects. The eventual extra noise caused by the MRI intervention itself is normally temporary. The noise sensibility of the area might however be important an important factor in determining the work times, with certain restriction put in place to minimise the disturbance. Improvement options on the other hand might generate a permanent rise in traffic levels and worsen the existing problems by increasing the intensity of the noise and the number of people affected. The expenditure with special noise protections in cases like this might be private but, following the tradition in the area, these costs will be assumed as environmental costs and will not be attributed to the individuals suffering them. This approach is substantiated by the fact that many countries have provisions to refund people affected by these effects. In the U.S., for example, there are provisions for the concession of special grants for soundproofing if the resultant noise during road upgrades grows to more than 68 dB (mean of 18 hourly values measured during the period from 6 AM to midnight on a working day) in houses within 300 metres of the road [FHWA, 1997]. This kind of measure demonstrate that the assessment of environmental impact will become necessary not only in new constructions but also in the maintenance of the existing infrastructure, since they can affect the expenditure and therefore change the cost-benefit balance. Noise is one of the most important of these impacts, as follows.

5.6.2 Impacts on the Environment

The potential scope of environmental costs resulting from traffic related works is very large and may include things like loss of land, damage to local fauna and flora habitats and visual pollution. However, due to the transitory character of Bridge Maintenance operations, the discussion of environmental costs in this study will be focused on two of its main components - atmospheric pollution and noise emissions. This is in line with the classification of main environmental impacts for bridgeworks provided by Mackie [1998].

Studies point out that road traffic noise is the most common source of noise, affecting 92% of dwellings in England and Wales with intense noise levels coming from motorways affect around 2% of these dwellings [Royal Commission on Environmental Pollution, 1995]. Over 505 sites registered noise levels higher than 55 dBL_{Aeq} (mean level of the sound over the recording period) with 7% being exposed to more than 68 dBL_{Aeq}. People are annoyed by this level of exposure, as demonstrated by a survey carried out by the Department of the Environment [Royal Commission on Environmental Pollution, 1995], where almost half of the respondents complained about the road traffic noise. The Royal Commission considers that the current levels of exposure are not strong (loss of hearing is usually associated with the exposure for long periods to levels of more than 75 dB) or continuous enough to result in hearing loss, but advises that many stress-related health problems can be associated with the current levels of exposure, specially when disturbance of sleep patterns occur. The impact of noise is not so serious in relation to Bridge Maintenance because of the temporary character of the work [FHWA, 1997]. It is however advisable to reduce noise when possible due to the discussed sensibility of the public to this problem. Improvement schemes deserve special attention because in these cases, as discussed before, the change in the characteristics of the bridge could originate permanent elevations on traffic and noise levels and extra expenditure would be necessary to minimise this impact.

In relation to atmospheric emissions, there is a growing awareness about the harmful effects associated to the gaseous discharges from petrol and diesel engines [Royal Commission on Environmental Pollution, 1995]. This fact has prompted the emergence of a series of regulations regarding maximum acceptable pollution levels, or equivalent congestion levels. Some research undertaken indicates that the pollution originating from traffic can be already causing serious health problems. Fortunately, there are signs that changes in the technology of newer cars has improved the situation and that emissions are no longer increasing [Automobile Association, 1998b]. However, it is in congested areas that this trend is less significant. The reduction of the number of disturbances becomes therefore even more important because they develop into the bottlenecks of the process. This stance might ultimately affect the choice of MRI strategy and the impact of atmospheric emissions should therefore be considered in a Bridge Management System.

5.6.3 Incidence of Environmental Impacts

Users currently do not pay for the environmental impacts caused by its usage of transport facilities. Individuals affected shoulder the cost or, more frequently, by the whole of society, falling ultimately on the taxpayers that have to finance the corrective measures undertaken by the government. This scenario will probably change in coming years because governments are introducing legislation to make drivers pay directly for all costs of transport. Recently the UK government announced its intention of improving the procedures aimed at recovering the cost of hospital treatments from users. Congestion pricing measures are also being considered to charge users trafficking in busy inner city areas [DTER, 1998]. In other countries certain initiatives have already started to develop ways of internalising the environmental costs and introduce taxation mechanism to charge the user [Hesselborn, 1995; Navrud, 1995]. There might be some resistance to these ideas since, as discussed before, users believe that they already contribute more than enough towards the payment of the transport costs. However, the development of techniques to calculate the external impacts of transport could change this perception.

A side effect of the introduction of environmental taxes on users will probably be the stimulation of research in the area of the valuation of these impacts. This could help to establish reliable monetary values for these costs that could be used in the appraisal procedure. Vickridge et al. [1989] have proposed the use of line rental values based on a social view of costs to justify non-intrusive (trenchless) excavation techniques.

Other internalisation mechanisms through environmental taxes have already been proposed in some countries [Saelesminde, 1995]. These developments are expected to reinforce the idea that Bridge Management should learn how to consider these types of costs in the appraisal of MRI strategies. The examination of expert knowledge showed that experts already consider these facts, although in a subjective way. More structured methods to deal with them are recommended to ensure uniformity and clarity. Bridge Management Systems will have to evolve to respond to this demand, as discussed in the next item.

5.6.5 Determination and Usage of External Impacts

There is a large debate on how to consider the external costs of transport. The greatest difficulty in considering these impacts is related to how to value them, since they are mainly non-monetary impacts. The need to consider user cost has largely been accepted. They are not easy to measure but there are fairly structured ways to assess them, apart from the increase in the risk of accidents. Chapter 9 will discuss how to extend the value to include the potential user cost at collapse.

On the other hand, according to Hanley and Spash [1993], there is a belief in some circles that environmental considerations are not suitable to be included at all in monetary assessments based on CBA technique, like the COBA procedure used by the Department of Transportation in the UK. Nash [1990] is one of the authors that disagree strongly with the position, arguing that they should be valued explicitly otherwise they will just be considered implicitly. This thesis endorses the position defended by Thompson [1995] that it is vital to try to include in the CBA all factors that might influence either benefits or cost, even when imagination is necessary to assign monetary values to what at first sight might appear as intangibles. The author believes that this is one of the more important advances necessary in the process of decision-making in Bridge Management.

Current Bridge Management Systems are not very successful in considering external impacts. Many systems consider user costs because of detours but few of them consider the users costs associated with the risk of failure. Sometimes the procedures used to estimate the delays are also not very sound. Worse still, the environmental impacts, which may be an important parcel of the external costs, are rarely included in the existing procedures despite the fact that there are already guidelines to consider them in new structures [FHWA, 1997]. Considering the fact that, as emphasised in chapter 4, there is a rising concern about the environmental degradation this thesis advocates that the environmental impacts should be considered more formally in Bridge Management Systems. This aim, associated with the recognition of the limitations of the existing systems (that will be explored in chapter 6), support the argument that it is necessary to explore new ways of considering the external costs in the appraisal of MRI strategies. This is the main reason behind the investigation into an improved appraisal model that will be carried out in chapter 9.

To consider the external costs in the economic analysis using CBA it will be necessary to develop ways to assess their monetary value. Appendix II presents a discussion about possible ways to establish values for "non-monetary economic goods" such as time, human lives, emission and noise. Reference values for each of them are established based on the examination of recent researches published and on experiments conducted using the valuation techniques discussed previously.

5.7 SUMMARY

The chapter established the important role of CBA in the decision-making process related to the appraisal of MRI strategies for Bridge Management. It analysed the origins, structure and limitations of the method and discussed various possible models for the comparison of costs and benefits, concluding that the ratio NPV:Cost is the best formulation for ranking projects with limited budget. The various impacts caused by bridge deterioration were then examined and it was argued that all impacts should be considered if a reliable expression of the social value of MRI strategies is to be obtained. Emphasis was given to the role of the external impacts, especially the negative effects on users and the environment. It was pointed out that these impacts are not being properly considered in current examples of Bridge Management Systems. Since the internalisation of these impacts is defended as vital for a proper appraisal, the introduction of new procedures to assess them was proposed. To do this it will be necessary to impose monetary values on the impacts and, since they are usually of a subjective nature, certain valuation methods were discussed. Prominence was given to the stated preference methods, which are already being utilised in some countries to extract values to be used in this way.

Need and Opportunities for the Production of Advanced Bridge Management Systems

6.1 Introduction

The consolidation of concepts carried out in the initial chapter provided the background for the critical evaluation of the status quo that will be carried out in the current chapter. This evaluation is based on several aspects, such as the analysis of opinions of experts from Brazil and the UK, the examination of technical problems associated with current practice and the discussion of structural and operational limitations of existing systems. The analysis establishes the need for the enhancement of Bridge Management Systems and illustrates the existence of opportunities for change, subsidising the validity of the main aim of the thesis, which is to investigate the possibility of advancing the development of these tools.

6.2 Establishment of the need for Change

Bridge authorities are increasingly considering the adoption of Bridge Management Systems as a result of the growing awareness about the need for a structured approach for Bridge Management or, in some cases, because they are being coerced by legislative pressure in this direction, as discussed in chapter 3. However, the dissemination of these systems has been frequently hampered by doubts about their ability to live up to the requirements imposed by real life situations and effectively satisfy users' needs and expectations. The analysis carried out in this chapter investigates the reasons for such beliefs.

Three main sources of information were used to collect data for the critical analysis. Expert opinion was elicited, the literature was reviewed and feedback from users was examined. To analyse this data a five-step strategy was devised, as seen in figure 6.1.

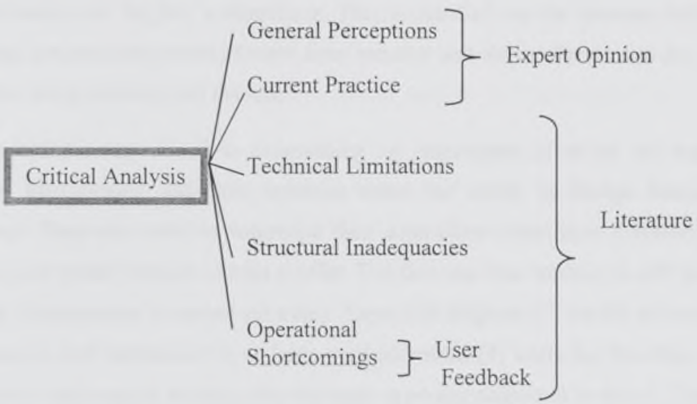

Figure 6.1 - Sources of Information and steps of the critical analysis exercise.

In the first step the general perceptions of the group of experts about the importance of Bridge Management and the utility of Bridge Management Systems were collected and discussed. The knowledge of the experts about how certain Bridge Management practices are carried out by the authorities to which they are linked was analysed in the second step. Later, based on a careful examination of opinions recorded in the literature, some of the most important technical problems associated with each stage of the Bridge Management process were identified. Inadequacies identified in the structure of existing systems are also discussed. Finally, an examination of the difficulties observed during the implementation of Bridge Management Systems in practice is undertaken, based on available feedback from users and occurrences documented in the literature.

6.3 STEP 1: DISCUSSION OF GENERAL PERCEPTIONS

A series of questions regarding various aspects of Bridge Management and Bridge Management Systems was posed to experts from Brazil and the UK during the series of interviews carried out to elicit expert knowledge described in chapter 1. Ten experts from different backgrounds were used, as described in Appendix I. This was considered as an adequate number to confer a suitable degree of representativeness to the results obtained. The opinions elicited from the group of experts are discussed below. Depending on the topic being analysed, the results are aggregated in different ways, with sub-sets of the group of experts being defined, such as academics x practitioners and English x Brazilians. This is justified by the inherent differences existing between the points-of-view from practice and the academia and the distinct realities faced in Brazil and the UK.

The questions were aimed at determining the importance given by the experts to Bridge Management and their opinions about the utility of Bridge Management Systems. They also tried to determine their aspirations about how a system should behave and which features should it offer. The first one was concerned with how well Bridge Management is carried out today. Experts in England (7) tended to believe that the issue is well addressed (3) or fairly well addressed (4) while the Brazilian experts (3) were unanimous in thinking that the topic is poorly addressed in Brazil. This result seems to be in accordance with the different degrees of importance given to the topic of maintenance in both countries, as discussed in chapter 3. It is interesting to highlight that commentaries associated with this question showed that there is a common trend between all the experts towards considering that an inadequate amount of resources is being allocated to Bridge Maintenance. Except for a single English respondent, all practitioners complained about the lack of sufficient human and monetary resources to undertake their activities. This seems to indicate that, despite the fact that maintenance is more valued and more structured in the UK, the constrained financial panorama of modern economies is making it difficult for authorities in charge of bridges in both countries to obtain adequate resources to finance their activities.

Another question posed to the experts explored their knowledge about which kind of management structure the authorities were they worked adopted. All practitioners (7) reported the existence of some kind of structured system for Bridge Management. Four of the English practitioners (5) used some kind of computer-based system while one expert reported just the use of a set of procedures. In the majority of cases (3), the computer system was the result of in-house development. These systems were described mainly as database driven and would probably be classified as First or Second Generation Bridge Management Systems. Just one of the English experts reported the use of a commercial system (which was linked to a GIS tool). One

Brazilian practitioner described the use of a computer based prioritisation system by its authority. However, while praising the system for its utility and because it is a pioneering initiative in a area were there is no tradition of structured management, he considered it still to be a rudimentary and fragmented tool when compared with the state-of-the-art Bridge Management Systems being introduced by other countries. The expert also emphasised the fact that the system was planned to be more comprehensive but reported that, during the inception phase, political and technical resistance has hampered its development.

Further questions were directed towards assessing the opinion of experts about the utility of Bridge Management Systems and determine the interest of the authorities represented by the experts in implementing them. The results show that, in general, commercially available Bridge Management Systems such as PONTIS are not well known or considered as very valuable by the practitioners. Both practitioners from Brazil considered their experience with commercial systems as insufficient to judge them. Between their English counterparts, two have received some previous information on PONTIS during a Bridge Management course but do not have a formed opinion about this type of software. From the rest, expert E considered commercial Bridge Management Systems as of medium utility while expert C considered them as of little value, but both did not have much experience with such systems. Expert D, a practitioner who had previous experience with a commercial system developed in England, considered that specific system as poor but still maintained a good impression about the utility of such tools. The academics were more positive about the usefulness of these tools, with all three of them considering commercial Bridge Management Systems as useful tools. However, they pointed out to the existence of serious limitations in current systems.

In relation to the general importance of having a Bridge Management System available, the opinion between English practitioners was divided. Two of them thought that Bridge Management Systems were of low importance to their activities, while other two considered them as of medium importance. It is interesting to note that expert D, which was the only one that had some previous experience with a commercial software and did not held a good opinion about it, nonetheless considered the implementation of a Bridge Management System as being fairly important to effective Bridge Management. Both Brazilian practitioners considered the need for a

Bridge Management System as important, even without having previous experiences with commercial or fully functioning systems. The academics (3) considered Bridge Management Systems as important (1) or very important (2).

Finally, regarding the interest in developing a system or implementing a commercial system in the near future, three of the practitioners in the U.K. (5) considered it low or fairly low, while two considered it medium or fairly high. In Brazil, the interest was high to both experts. This question was considered irrelevant to academics.

6.4 STEP 2: EXAMINATION OF CURRENT PRACTICE

The second set of questions was directed towards determining which are the Bridge Management practices adopted in practice by bridge authorities. Because of this fact, the analysis of the results concentrated just on the responses from practitioners.

In relation to which method is used to asses the condition of bridge elements, all English practitioners (5) reported the use of historical data, bridge inspector's assessments and expert opinions. No expert used deterioration models but two of them have had some experience with trend analysis or pattern identification. In the comments' section, expert A reported the additional use of specifications while expert E emphasised the role of engineering judgement. In Brazil, both experts said that they relied primarily on expert opinion. There was some dispute about the usefulness of historic data, with four of the practitioners considering it as very or extremely useful and three others considering it just as useful or fairly useful. Expert opinion and bridge inspector assessments were considered as very useful methods by all interviewees (7). Three experts classified deterioration models as fairly useful, while the rest (4) consider that they did not have enough experience with them to assess their usefulness. The experts also considered trend analysis as useful (4) or fairly useful (3).

In relation to the costing of maintenance activities, three English experts reported the use of unit costs while two others relied more in estimates given by contractors. Contractors are also the main source of cost information for one expert in Brazil. The second Brazilian expert reported the use of unit costs and expert opinion to define the expected costs of major works. None of the practitioners reported the use of any kind of structured cost analysis technique to calculate maintenance costs. This indicates that costing is still being addressed in a very rudimentary manner, prone to create large inaccuracies in terms of budget definition. When inquired about this fact, all practitioners agreed that the current approach was inaccurate (5) or very inaccurate (2).

In relation to the selection of maintenance strategies, just one English expert reported the use of economic information, in the case basic cost estimates, to help determine the appropriateness of undertaking a certain course of action. All others (6) reported the use of engineering judgement, experience and analysis of the results of structural and functional assessments as the determinants for the decision of if and how to intervene.

Regarding the assessment of the benefits of maintenance, all English practitioners (5) reported the use of cost-effectiveness analysis (CEA). This is the only criterion adopted by expert D. Expert E also uses some kind of network optimisation criterion while expert B prefers to combine CEA with cost minimisation and value analysis. Expert C combines CEA with network optimisation and cost minimisation, while expert A uses all techniques plus cost-benefit analysis (CBA) but do not carry out network analysis.

Figure 6.2 shows the aggregated score given by the experts to the usefulness of each one of the various appraisal techniques. Just the opinions of the English practitioners were utilised because the Brazilians considered that they did not have enough knowledge of all methods to produce a balanced opinion.

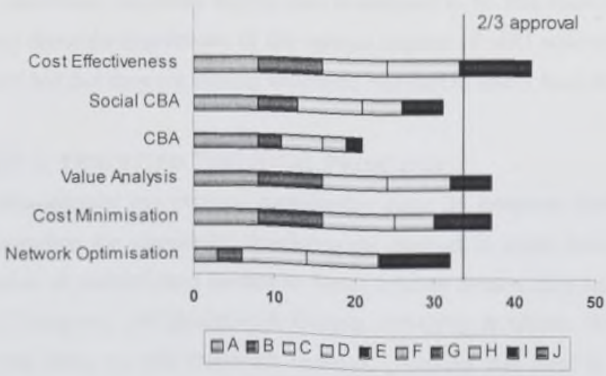

Figure 6.2 – Importance given by the experts to various methods of benefit assessment.

The results show that cost effectiveness is considered the most useful method. The majority of the respondents also approve the use of value analysis and cost minimisation. This seems to suggest that simpler methods, where the reduction or optimisation of monetary resources is the dominant objective, are still the preferred ones. The more sophisticated methods used in Third Generation Bridge Management Systems, such as network optimisation and social cost/benefit analysis, are in general not seen as very adequate by the group of experts interviewed. This may be attributed to the fact that these methods are not so easy to use and demand considerably more information. It is interesting to highlight, however, that the experts that actually use these methods considered them to be very useful.

It can also be verified that the majority of experts considered purely economic CBA as inadequate. This result confirms the belief of the author that there is a growing awareness about the need to consider a wider spectre of impacts when assessing benefits. The fact was in evidence in the next question, where information about what types of costs were considered during the analysis of maintenance strategies was elicited from the seven practitioners. Three experts considered third-party costs in some form, while just two of them considered environmental and congestion costs. One expert reported an attempt of internalising user costs, but commented that the procedures are still rudimentary. Four experts reported that all the various cost factors were taken into consideration, but in an unstructured manner, which means that they are not quantified. The main finding was considered to be that there is considerable awareness about the importance of the various impacts of MRI actions by the part of the experts but that they are lacking structured methods to assess them in a proper way.

6.5 STEP 3: PERCEIVED TECHNICAL PROBLEMS

Bridge Management has evolved considerably since its inception [Itoh et al. 1997]. Notwithstanding the significant developments attained in some areas, such as the construction of sophisticated models to forecast future deterioration using Markovian Chains [Thompson, 1993][Scherer & Glagola, 1994][Ng & Moses, 1996], this thesis argues that there are still important technical problems that need to be addressed. Following a detailed examination of the literature and using the insights obtained with the study of PONTIS and the discussions with experts, the following list of technical limitations and problems associated with the Bridge Management process was identified:

- amount of data collected
- format of data collected
- imprecision of the techniques for assessment of bridge conditions
- rigidity of compliance criteria
- difficulties associated with the forecasting of deterioration
- lack of relationship between reliability indexes and condition states
- inadequate mechanisms for the selection of the best choice of maintenance option for each element
- scope of the economic appraisal exercises
- absence of efficient work packaging techniques
- lack of feedback and control

The author believes that, while not exhaustive, the list is as complete as possible and is a fair representation of the major questions surrounding Bridge Management practice today. Each of these perceived problems will be discussed in greater detail below.

6.5.1 Format and Scope of Data Collected

One of the problematic issues indicated in the literature and discussed by experts is related to the amount of data collected during inspections. Some authors believe that the data being collected by some authorities today might not be sufficient to ensure that all the relevant information for the management of bridges could be extracted [Turner & Richardson, 1993]. The problem originated from the fact that the amount of data necessary to support the Bridge Management activities has grown exponentially as a result of the emergence of Bridge Management Systems. In 1988, the FHWA issued the 4th edition of the *Recording and Coding Guide for the Structure and Appraisal of the Nation's Bridge* [FHWA, 1988]. This publication established the minimum needs for data collection by the states to supply the National Bridge Inventory (NBI) in the U.S. and suggested the collection of 16 items plus condition and appraisal ratings. It was forewarned however that, to develop a data base that could adequately support a Bridge Management System, it would be necessary to collect several additional items. More recently, a survey of data collection practices of various states in the U.S. found out that this prediction was correct. On average, states were collecting around 280 items but several collected more than 400 items and New York reached 700 items [Turner & Richardson, 1993].

The need for more data was mainly triggered by the necessity to support several additional activities being carried out, such as deterioration modelling, maintenance selection and optimisation of funds. The continual sophistication of such methods and the increase in the role of the computer as a decision-support tool has meant that the demand for new data has grown steadily in the last few years and will probably continue to do so in the near future. Many systems do not provide good data management facilities nor allow the easy updating of models to take into account the new data and/or the new knowledge made available. More flexibility and sounder data management structures are seen as a necessary advance. Alternative means of automatic data collection might also be interesting since the gathering and maintenance of data is time consuming [Andersen & Lauridsen, 1993], there are usually problems with the translation of forms to the computer and authorities are normally short of manpower.

6.5.2 Format of Data Collected

It could be said that the most vital data items being collected are the ones that express the condition of the bridge structure. The whole management process in modern systems is based on the analysis of the present condition of bridges and the forecast of future deterioration based on these conditions and the local environment.

The problem is that sometimes a unique rating is collected for each of the main three sub-systems of a bridge (deck, substructure and superstructure). This procedure is advocated in the Sufficiency Rating criteria proposed by the FHWA [FHWA, 1988] and was adopted by many of the older Bridge Management Systems. The author considers that the use of aggregated values like these are not suitable for the appraisal of the bridge because the information is too agglutinated to be of great use. The adoption of the concept of elements, as implemented in Third Generation Bridge Management Systems like PONTIS [Thompson, 1993], has partially helped to overcome this problem. Bridge authorities are showing their preferences to this approach and Das [1997a] has already defended the incorporation of the concept of elements in the development of the BMS being undertaken by the Highways Agency in the UK.

The concept of elements means that, instead of having a single grade for the whole bridge or the main sub-systems, information is collected at the element level. This means that it is possible to trace deterioration patterns specific to each element and discuss maintenance strategies appropriate to them. However, the use of the concept of elements as is done in PONTIS does not solve completely the problem. It is not sufficient to know that 10% of the columns in a bridge are in bad condition, but it is also necessary to be able to identify exactly which are those columns that are in bad condition. This can have an impact on the determination of the cost of rehabilitation, for example, because some elements are much easier to repair than others because of different access conditions.

One of the ways to overcome this problem would be to maintain a register of the specific characteristics and of the condition of each element. Data would just be aggregated when necessary to carry out network analyses. New procedures to calculate the cost taking into consideration the characteristics of the element is another possibility for improving Bridge Management Systems that could be investigated.

6.5.3 Techniques for Condition Assessment

According to Aktan et al. [1996], the use of subjective or inaccurate condition assessment techniques has been identified as one of the most critical barriers to the effective management of bridges. Various articles have discussed this topic, such as McCracken [1996]. The question is that, as discussed in chapter 3, the great majority of Bridge Management Systems do not use the data about bridge defects directly. A conversion scale is usually adopted to transform the deterioration data into some kind of numerical index that indicates the Condition State of a particular element. These scales are designed to represent the evolution of the condition of an element over time and are the result of a division of the continuous deterioration curve into a limited number of defined stages. The first problem associated with this practice is that it produces results in the form of discrete ordinal measurements. As explained by Madanat et al [1995], this means that the numbers assigned do not indicate distances between ratings, but only a relative ordering. They therefore recommend that care must be exercised to avoid using these values out of context.

Another problem concerns the definition of the various deterioration stages. As discussed by Vassie [1997b], the most accepted way today of establishing the boundaries between condition states is to base them in changes in some observable characteristic of an element so that an inspector could easily classify the damages encountered. This practice means that certain points in the deterioration process that are characterised by easily observable effects, such as the beginning of flaking or the appearance of rust marks in the surface of the concrete, are usually chosen to mark the transition between condition intervals. While this reduces the uncertainty associated with the grading of the condition of the elements by the inspector, it might go against the idea that condition states should be associated with changes in risk thresholds.

The problems surrounding condition assessment are compounded by the fact that several defects can occur simultaneously in one element. A concrete pillar or a column might have corroded zones at the same time that it is suffering from alkali-silica reaction or showing signs of structural distress. It is usually very difficult in such cases to attribute a unique value for the Condition State. It is necessary to determine the relative importance of the defects and assess their combined effects. This is normally a subjective procedure and the final result could be misleading. Furthermore, a fair degree of information is usually lost during this aggregation process. This is a serious problem when the need for choosing a treatment arises. The treatment that should be applied to such an element would be complex, probably combining elements from the specific treatments used to deal with each one of the individual conditions present.

6.5.4 Compliance Criteria

The main problem associated with the verification of compliance is the occasional rigidity of the compliance criteria, especially in relation to structural assessment [Brodie, 1997]. As pointed out by Clark [1997], a bridge that fails an assessment exercise is not necessarily inadequate. It might be possible to apply non-code analytical techniques or specific test data to demonstrate that the bridge is acceptable. Or, in some cases, it is possible to adopt interim measures to minimise the problem, postponing the need for strengthening [Das, 1997d].

To allow an BMS to fulfil their role in helping human decision-makers select the most appropriate (or value maximising) strategy, its is necessary to let the software analyse various possible alternative courses of action. Following the philosophical stance discussed in chapter 4, safety must be understood as a component of bridge value and not as an imposition from the legislation. The Highways Agency (HA) in the UK has already realised that there is a need to change current assessment rules to provide more flexibility, as explained by Das [1997e] but more emphasis is necessary to change the paradigms currently adopted.

Another limitation is that sometimes only items related to the structural condition of the bridge are verified. Since the main function of the bridge is to sustain the transportation function, as suggested in chapter 2, other items linked to the performance must also be analysed. Fortunately, the majority of Bridge Management Systems in operation today has recognised this need and incorporated tools for verifying operational items such as minimum width, road alignment, water clearance etc. However, due to the increasing importance given to environmental factors, as discussed in chapter 4, it might soon be necessary to extend existing criteria to include less common items such as the performance of noise reduction elements. Aspects relating to functional obsolescence, as suggested by Branco and Brito [1996], might also have to be considered.

6.5.5 Condition Forecast

Forecasting of deterioration is a vital part of the decision-making process in the most sophisticated Bridge Management Systems currently in operation. As explained in previous chapters, the selection of maintenance activities is becoming increasingly dependent on the examination of the effects of different courses of action in the future state of the structure and the network. Predictive deterioration models are not considered precise enough to provide the information necessary for the analysis and probabilistic models have started to be introduced in systems such as PONTIS. These models are based on the concept of Markovian Transition Chains and, according to Madanat et al. [1995], are more realistic representations of the deterioration process. Nonetheless, there are some serious problems that affect this procedure.

The first problem is related to the establishment of Transition Probabilities (TP). The determination of the probability of each element changing states is vital since the whole idea of Markovian Chains is conditioned to the availability of these probabilities but Vesikari [1992] emphasises that the transition probabilities are not always easily calculated. Expert opinion has been used to produce a first estimate of the TP [Golabi et al., 1993]. This is however a very subjective practice and a more structured analysis of the deterioration patterns is usually considered as necessary.

A more structured approach denominated as "expected-value" method divides the facilities in sub-groups and constructs deterioration models using linear regression, with age normally being adopted as the independent variable. The TPs are estimated by minimising the difference between the expected value of condition rating as predicted by the model and the theoretical value derived from the structure of the Markow chain [Madanat et al, 1995]. The problem with this approach is tha' the absence of reliable data about the deterioration of a bridge can make the effort of determining performance patterns not viable. Regular inspection efforts have just been started in the late 60's and therefore, in the best circumstances, the maximum amount of data stored would be around thirty years old, less than one third of the proposed bridge lifetime of 100 years [OECD, 1981]. In this period, the type and quantity of data recorded has also changed. It is therefore very difficult to have enough consistent data to trace a performance curve for any specific bridge.

Even when data about the deterioration of a particular bridge exists and is available, it should be seen with caution because several factors contribute to alter the performance of the bridge over time, such as increases in the weight of trucks or in the number of vehicles passing on the structure and variations on the environmental conditions (e.g. increases in the acidity level of rainwater or changes in the patterns of de-icing salts usage). This means that the future deterioration of the bridge can follow a very different path from the one registered until now. The problem is compounded by the fact that, during this interval, elements of the bridge have aged or been replaced, adding to the uncertainty about the future performance.

Data from similar bridges is sometimes combined to help establish general performance trends. This is an useful practice but it can also be misleading because nothing ensures that the deterioration curve in two structurally similar structures will be the same. The terrain conditions, the materials used, the workmanship during construction, the different conditions on each site, the different functional parameters - i.e. intensity of traffic, percentage of trucks, speed average, etc - are just some of the factors that could warrant the existence of important differences in terms of deterioration behaviour. Despite this problem, the combination of data from bridges of a similar type to determine generic patterns of deterioration behaviour is still considered to be the best alternative available to establish the TPs. The results should however be analysed with caution and be checked against the inspection data collected whenever possible to verify their consistency.

Madanat et al. [1995] additionally criticise the stationary nature of the current methods for determining transition probabilities. They consider that the existing procedures do not capture the essence of the structure of the deterioration process and therefore are not able to explicitly model the changes in condition from one point in time to the next. They also consider that the latent nature of deterioration is sometimes misguidedly confounded with the observable distresses, which are in fact manifestations of the true deterioration.

Another problem surrounding the establishment of TPs is related to the synergetic effect of deterioration mechanisms. One of the main limitations of the routines encapsulated in the software PONTIS is the fact that the deterioration probability of each element is considered independent from the deterioration of surrounding elements. In practice, defects in a single element could have influence over the performance of other elements, by means of a superposition of effects. Deterioration of joints will enhance the probability of deterioration of bearings and pillars located behind them. This may be addressed by the adoption of notion of local environments and the calculation of different transition probabilities depending on these environmental conditions. The Finnish Bridge Management System adopts a correction coefficient K that represents the shortening in the expected lifetime of an element in poor condition (condition state 4) because of the existence of another defects [Vesikari, 1992]. However, the restriction of this analysis just to elements in condition state 4 (very poor), the reduced number of damage types considered and the fact that the K coefficients are calculated using expert opinion limit the usefulness and generality of this approach.

The final shortcoming perceived by the author and linked to condition forecast is related to the assumption that, after the undertaking of the maintenance operations, the probability of deterioration of the element will remain the same. It is fair to suppose that rehabilitated elements could behave in a different manner than the original elements and this fact should be taken into consideration.

6.5.6 Determination of Risks

The lack of a consistent application of risk analysis techniques during the process of Bridge Management due to the fact that many systems do not have specialised routines to support this activity was seen as the first limitation in terms of the determination of risks. Another problem diagnosed is related to the scope of risks considered. The risk analysis frequently is limited just to the structural risk of failure or the risk of accidents to users because of inadequacies of the bridge. Mechanisms to quantify other less evident but also important risks, such as the risk of economic losses associated with the functional disruption of the Transportation Function or the risk of injury to passers-by because of minor deterioration, should also be developed. The major problem in the opinion of the author, however, is that condition states are normally dissociated from the notion of risk. To allow the calculation of benefits from maintenance it would be useful to correlate each Condition State with a certain degree of structural or functional risk. To achieve this it is necessary to redefine the scale of Condition States using a reliability approach. The boundaries between states should not be defined anymore by observable changes in some distress parameter but by changes in the reliability index.

6.5.7 Selection of Maintenance Options

The author found out that it is not uncommon in current practice to associate a unique solution to each problem. This approach ignores the fact that there are usually several different ways to tackle a problem whose utility might vary depending on the characteristics and location of the defect and the type and condition of the rest of the structure. The definition of a unique and standard solution to a problem might not be the best alternative. An associated limitation is that current procedures ignore the interaction between bridge defects. A careful mix of activities, combined to obtain adequate results, might be necessary to solve the various problems of an element. It might be necessary to take this into account to improve the performance of Bridge Management Systems in this area. Standard maintenance packages and prices can be used as an approximation of the cost, specially when more detailed information is not available, but the limitations of this choice must not be forgotten.

Alternative courses of action should also be defined because during the prioritisation exercise it might occur that the preferred action for a particular bridge is not included in the list of actions that will be executed in the first budgetary period. The choice of the best strategy must then be remade knowing that the preferred action is not possible and that intervention will have to be delayed to a certain time in the future.

6.5.8 Appraisal

The first problem to ponder in this case is related to the scope of the impacts to consider in the appraisal analysis. The key to successful management of private projects consists in making the best use of the available resources and maximise profit, as suggested by Smith [1998]. However, in the Public Sector it is necessary to have a wider view. As put by Mackie [1998a], in an appraisal exercise carried out by the government it is not sufficient to consider just the economic aspects but also the social and possibly the political aspects of the problem. As pointed out by AASHTO [1992], Bridge Management could benefit for example from the introduction of the capability to compute the congestion delay associated with different types of bridgeworks during various periods of the day.

The author also identified some important issues connected to the determination of the impacts of bridge deterioration and maintenance. The first problem is related to the quantification of the work to be done. It is common to verify that that the amount of work to be carried out could not be properly estimated until the deteriorated areas are cleaned and prepared for maintenance. The second problem is linked with the use of standard unitary costs to calculate the cost of a certain maintenance option. This is a common approach in various systems but it can distort enormously the cost, because the agency expenditure will in fact depend on various specific factors such as the access conditions and the complexity of the traffic management measures necessary. The author considers that it is necessary to widen the assessment of cost. This stance is supported by observations from Itoh et al. [1997], who complain about the lack of a stronger relationship, in conventional Bridge Management Systems, between bridges and other elements that strongly affect bridge maintenance, such as roads and rivers.

Apart from the inaccuracies in calculating the agency expenditure, there are also difficulties in estimating the monetary values for the social cost of maintenance. As seen in chapter 5, many external costs are not easily measured, especially those related to environmental and society costs. These impacts are frequently assessed just on a qualitative basis because of the difficulty in quantifying the effects to the users, the authorities in charge of the structures and the society in charge [Falls et al, 1993]. However, as emphasised in chapter 5, this thesis argues that the economic appraisal should be based on the use of social CBA, which is in turn dependent on the determination of the monetary expression of costs and benefits. The establishment of a structure that could facilitate this undertaking is one of the suggestions for improvement that will be discussed in greater detail in chapter 7.

Finally, there are also questions posed about the scope of benefits to consider. Current systems such as PONTIS have already recognised the importance of assessing user benefits when deciding which actions to undertake [Thompson, 1993]. The problem is that the existing procedures limit the analysis of benefits to the cost avoided if you can prevent accidents or load and clearance restrictions on a bridge. It does not extend the concept of benefits to the analysis of the MRI intervention in itself and its full effect in terms of the utility of the bridge.

6.5.9 Disregard for the benefits of work co-ordination

Another important technical limitation of Bridge Management practice as encapsulated in existing systems is the lack of an instrument for analysing the benefits of combining maintenance operations in order to create more rational projects that would optimise the use of the resources of the bridge authority. This is still done informally by bridge engineers. However, as pointed out by AASHTO [1992], this is one of the main enhancements that can be expected to strengthen current BMS software. According to them, a well-structured work packaging routine could help improve the process of setting priorities and would facilitate the co-ordination and the scheduling of related projects.

6.5.10 Lack of Feedback

The final problem diagnosed is the absence of a structured feedback mechanism. A great degree of information might be lost because of this. In the U.S., states are now obliged to maintain certain historical data, but there are much more information, especially about costs and the circumstances surrounding decision-making, that could be helpful in informing new decisions. It is necessary to establish procedures to let systems "learn" from previous experiences.

6.6 STEP 4: Limitations of the Structure of Existing BMS

Beyond the existence of various technical problems that affect the procedures encapsulated in the analytical core, as discussed in the previous section, this thesis considered the possibility that the structure of existing Bridge Management Systems is also becoming inadequate to fulfil the requirements of modern Bridge Management. The author tried to identify the main shortcomings and examine the changes that are deemed necessary in order to improve existing systems.

6.6.1 Data Collection

According to Turner and Richardson [1993], data collection is becoming the most important bottleneck of the bridge management process. The introduction of sophisticated routines has increased the necessity of collecting more data, as discussed before. Sriskandan [1991] emphasises that the reliable production of information is the most vital requirement for establishing a successful Bridge Management System. However, if the quality of the data collected is not adequate, the production of adequate information is not possible. Unfortunately, existing systems do not provide much help to ensure that the best possible data is collected. The problem is that current systems do not have a well-developed data collection component. Better mechanisms of data collection could improve the efficacy of the inspection phases, diminishing the chances of loss or corruption of information during the transmission process from the field to the database. Paperwork damage; misleading interpretations of field scribbling or diagrams; losses of data and typing errors are just some of the occurrences that could be expected to happen some time along the process of undertaking repetitive and continuos inspections of many bridges.

Beyond incorporating more specialised routines to support inspection, the data collection components will also have to be adapted to deal with a broader spectre of types of data. As pointed out by the FHWA [1997], new systems will require the collection of additional items not contemplated in current guides. This will probably include a lot of data of a graphical nature [Shroff & Nathwani, 1997][Gomez-Rivas & Lopez, 1997]. This will impact the data storage component, as discussed below.

6.6.2 Data Storage

An important shortcoming of existing systems is the limited ability to deal with non-textual data. Traditionally, various types of data are collected during inspection. Several of these are graphical in nature, such as drawings, sketches and cracking maps. A reliable assessment of the conditions of each element and the potential treatments can normally only be done by combining all these elements. Since Bridge Management Systems are gaining greater responsibility in supporting this type of decision-making, there is a growing need for systems that are capable of handling this multitude of data. Multimedia Bridge Management Systems have already started to be developed [Shroff & Nathwani, 1997] and future systems will probably be expected to be able to store and display data in various formats. Das [1997a] reported the intention of transforming the national inventory in the UK (National archive of Transport Structures - NATS) by allowing the inclusion of topographic, video and virtual reality media. The revised database is expected to be one of the basic elements of a new Bridge Management

System being articulated by the Highways Agency, denominated SMIS (Structures Management Information System).

The increase in the amount of data being collected is also prompting a rapid expansion of the size and complexity of databases. There will be necessary to find adequate ways of co-ordinating the management of the large amount of data arriving from many different sources, like traffic statistics and accident information. The use of a unique database will probably become unfeasible because of administration and security problems. A distributed structure will likely emerge, where various databases will have to be co-ordinated. It will be important to develop reliable ways to co-ordinate the management of these various bases of data in order to create a smooth and coherent flow of data and prevent errors and confusions. The emergence of new communication possibilities such as the Internet will make these advances even more important.

6.6.3 Interface

In terms of the interface component, the main shortcoming of existing systems is the lack of a more natural interface for presenting data to users. As pointed out by Bracken and Webster [1990], now that processing power has become relatively cheap the emphasis is shifting towards the development of user-oriented systems and applications. The AASHTO [1993] discuss the need for an interface with the capability of presenting data in a user-friendly way and suggests the use of GIS technology to achieve this aim. The incorporation of a GIS component would have the added advantage of establishing a common platform for the integration of various infrastructure systems, as will be discussed in coming chapters.

6.6.4 Analytical Core

There are a lot of technical limitations and untapped potential for improvement in this component. The analytical core of existing systems is frequently missing modules to deal with important aspects of the Bridge Management process described in chapter 3. Some systems do not posses risk analysis tools while others do not support economic analysis or are unable to make network analysis, for example. Many systems lack reasoning capabilities and can not make use of the stored data and the available information to offer suggestions of strategies to the decision-maker. In some cases, the actual procedures encapsulated in the analytical core are limited and might need to be modified to produce more adequate systems.

Existing systems might also have to evolve in terms of the structure of their analytical core. The greatest reason for the failure of information systems is the incapability of adapting to changing realities in the organisations using them. This is potentially valid to Bridge Management Systems. It is important therefore to create a more flexible structure to improve their capabilities of functioning in real life conditions. This will be one of the main stems of the concept of advanced systems to be introduced in later chapters. Also, because a lot of research is being carried out in the domain area of Bridge Management, updating the existing models should be made easier, to allow the systems to be always in line with recent developments.

6.7 Step 5: Implementation and Operational Problems

According to Itoh et al. [1997], Bridge Management Systems have been undergoing a continual development over the last three decades. In this period a great number of systems has been proposed, developed, discussed and studied. Some of them have gone to become operational, while others have had limited acceptance or been abandoned. It is important to examine this feedback in order to understand how to produce systems that have a better chance of satisfying the requirements of users. It is vital to identify the causes behind the failure in effectively attending user's needs and try to understand how to avoid repeating these errors. One of the most common complaints expressed by users is connected with the rigidity inherent in the architecture of the current Bridge Management Systems. Some systems are not capable of performing with enough flexibility when it is necessary to tackle some of the most difficult issues related to the prioritisation and programming of bridge maintenance schemes. The lack of flexibility tends to make systems act in a deterministic and limited way. Users complain that systems of this kind are unable to cope with the subtleties of the process of Bridge Management, which is complex and involves many contrasting views, as discussed in chapter 3.

Another inhibiting factor for the dissemination of Bridge Management Systems is related to the "black-box" syndrome. This syndrome is characterised by the inability of some users to identify and understand, in a clear way, the procedures being carried out by the computer. This situation makes users perceive the system as a closed entity over which they have little control and small influence. Reynolds [1992] emphasises the importance of allowing the user to understand the models behind any Decision Support System – not just how to use them but also the basic assumptions on which they are based. Vaughan and Mitchell [1996] argue that no Decision Support System will function if it is perceived as a "black box" model, hiding key assumptions from the user. A side effect many times associated with the black-box syndrome, but that also appears alone, is the tendency to overestimate the accuracy of the results. This is the consequence of the tendency of certain users to trust implicitly the output from the system just because it is the result of fairly complex mathematical manipulations done by a computer and is presented in an organised and well designed format. These results may be given unduly consideration by users that do not fully understand the implications and limitations of the processing, inducing the adoption of false "assumptions", as pointed out by Carter et al. [1994]. In this case, the results of the computer processing are not analysed with a critical eye, as it always should be the case and the whole decision-making process then becomes distorted because the user does not have an active role in it. This kind of situation must be avoided because the underlying issue is that many times computer-based systems are fed with inaccurate, incomplete or simplified data. The intensive processing of this poor-quality data using complex mathematical manipulation would never produce reliable results. The fact is that a tool is just as effective as its user capacity to use it wisely, as pointed out by Reynolds [1992] and Smith et al. [1997].

The perception of lack of control caused by the "black-box" syndrome allied with the inability of some systems to adequately respond to the demands of a dynamic decision-making process due to their rigid architecture has prompted some organisations to undertake steps to reduce the participation of BMSs in their management activities. The use of parallel paper-based processes, which often override computer results and suggestions, is a common stance in these occasions. This is a very ineffective choice because the management work is in effect being carried out twice and there is the added risk of conflicting information being produced and disseminated, causing confusion and generating uncertainties in the organisation. The adoption of less sophisticated systems, resembling earlier generations of Bridge Management Systems, has been advocated [Darby et al., 1996] to resolve this impasse. The reduction of the computer role restores the control of the process to the user but prevents systems from becoming useful tools to support the complex decision-making activities typical of bridge maintenance problems.

Certain systems have also suffered because of the lack of a common architecture between their constituting parts. In some cases, the development of systems was gradual and indigenous with the various Bridge Management functions being automated at different times and being treated, at some stage, as independent systems. This means that there is no common design framework. This kind of fragmented, and many times disorganised, evolution of an information system in an organisation tends to create what Peltu [1989] describes as "islands of automation". This fact accounts for many problems related by Shroff and Nathwani [1995], who cite cases where different modules run on different hardware platforms and use distinct operating systems. The lack of co-ordination detracts from the need to have all the information readily available and orderly arranged to achieve the best performance during the decision-making process. It also makes the upgrading of the system a complex activity, involving sometimes a complete overhaul of the software structure and of the storage system to accommodate new routines or better models.

6.8 Summary of the Findings of the Critical Analysis

The analysis of expert opinions showed that there is a mixed impression about the importance of Bridge Management Systems. Practitioners tended to think that these systems might be interesting but they are wary of the work involved in setting up and administering a system like this. All experts concurred that there is need to improve existing Bridge Management practice and that computer-based systems can play an important part in it and have even started developing some in-house tools. There were however doubts expressed about the ideal structure for such tools. Experts that have had experience with some of the current commercial systems available considered them as inappropriate and in need of change. The analysis of the knowledge elicited about current practice highlighted several problems. One important issue is that cost analysis is still being done based on unitary costs. This practice can distort the budget determination and allocation. It was verified also that maintenance selection is being treated in a subjective way. This thesis argues that it is necessary to establish more objective criteria, based on the notion of value maximisation, as discussed in chapter 5, to guide it. To do this the author consider that it will be necessary to broaden the scope of impacts being assessed, since it was established that many authorities do not consistently determine user and environmental costs.

In relation to the examination of technical problems, the critical analysis has shown that there are several areas that need improvement. Two of the most important issues discussed in the opinion of the author were the ones referring to the difficulties related to the forecasting of deterioration and the limitations of the scope of the appraisal analysis. Other issues were discussed, such as the need to make the compliance criteria more flexible and the need to improve data collection and management procedures. The analysis also determined that the traditional structure of agency costs adopted in current systems is not adequate to represent the real cost of a maintenance operation. Additionally, the need for improved risk analysis procedures and more sophisticated work packaging methods was made evident. On the other hand, the evaluation of the limitations of the structure of current systems provided evidence that existing components will need to be re-structured. This will be necessary to allow them to fulfil new requirements deriving from the evolution in communications, the increase in data needs and the necessity of creating more user-friendly interfaces.

Finally, the evaluation of the more frequent problems occurring during the implementation and operation of Bridge Management Systems illustrated the fact that the current characteristics of these systems are not fulfilling user requirements. The difficulties faced are normally related to issues of acceptability, flexibility and clarity, which have not yet been addressed satisfactorily.

In view of these facts, the opinion of the author is that the critical analysis carried out support the establishment of the following considerations:

a) There is a need and a fair desire from practitioners to have a computer based system to help then deal with Bridge Management, but

b) Existing systems have a series of technical limitations, both in terms of the procedures encapsulated as well as the structure of its components, and

c) Users are not completely satisfied with how existing systems operate.

This combination of factors justifies the main hypothesis of the thesis that further advancements are necessary. Not all the problems can be solved without extensive research and testing, but a proposal for a framework that will facilitate the production of enhanced systems will be presented in the next chapter. Fortunately, several factors seem to be combining themselves to support the idea of undertaking such changes, as discussed below.

6.9 The Momentum for Improvement

Markow [1995] argues that highway management systems are currently poised at a major stage of redevelopment, driven by changes in the way management, decision-making and information requirements are being redefined in transportation agencies. In fact, as suggested in figure 6.3, it could be considered that there is today a real momentum for improvement in the field of Bridge Management Systems resulting from a combination of existing needs and the emergence of significant opportunities for change. In the side of needs, the recognition of the limitations of existing software discussed in the previous section and the consequent user dissatisfaction both have been major motivating factors. On the other side, the possibility of effecting significant changes is growing since, as remarked by Parker [1996b], emerging technologies are opening new opportunities to collect, manage and analyse with greater accuracy and flexibility much more information than ever before. This concurs with the premise adopted in this thesis that rising IT technologies can considerably increase the capabilities of existing Bridge Management Systems, which will be explored in greater detail in the remaining parts of this thesis.

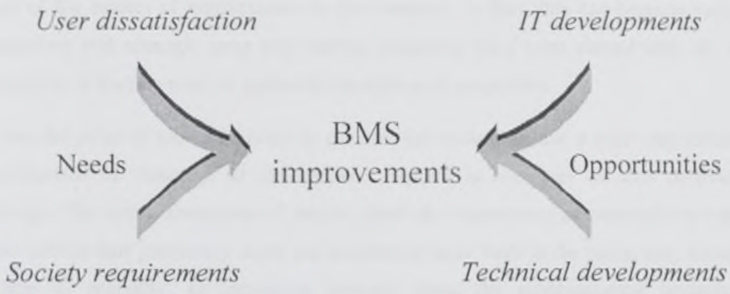

Figure 6.3 – Factors sustaining the Momentum for Change.

At the same time that IT is providing opportunities for the development of a new architecture, the great amount of research that has been dedicated in recent years to various aspects related to Bridge Management provides a sound basis for more theoretical changes. The experience collected and problems faced during the introduction and testing of Bridge Management Systems in practice have also provided an important feedback. A considerable amount of knowledge has been accumulated and is now available to help find ways to overcome some of the limitations discussed earlier. However, having the desire and the technical capability of producing a more advanced system would not be sufficient if there was no social and political motivation to implement the changes.

Fortunately, this motivation exists as a result of the fact that all the parts involved are showing growing interest in the subject of bridge maintenance. The momentum for change is reinforced by the realisation of the importance of maintaining bridges in operation. Aktan et al. [1996] report that the National Science Foundation (NSF) has in 1994 responded to the need of research in this area by allocating a $20 trillion amount to the development of studies concerning the topic of Civil Infrastructure Systems (CIS). Itoh et al. [1997] remark that the rapid growth of automobile usage combined with a slow expanding network capacity is highlighting the need for an improved management of highway elements - bridges in particular. Users are realising that, with rising congestion levels, it is vital to optimise MRI interventions in order to reduce unnecessary disruption and the undesirable effects associated with it. In this scenario, the adequate management of the network is considered a priority. Public authorities are also becoming more aware of the complexity of the problems generated by congestion and of the impact of maintenance in this scenario. In fact, this has become such an important and strategic issue that various initiatives have been started with the sole objective of finding ways to minimise the effects of congestion.

From the point of view of society in general, the realisation that a more sophisticated mechanism of valuation of maintenance impacts is necessary is also motivating change. The rising awareness of people about the importance of externalities means that effects that previously were not considered now have to be taken into account. There is, specially, an increasing concern about the environmental impacts of transport, as pointed out by the Royal Commission [1995]. This panorama is fostering the development of a series of new assessment methods to allow the quantification and consideration of such factors, as discussed in chapter 4.

The combination of needs and opportunities suggests that changes aimed at producing improved systems for Bridge Management would be well received. The question is to decide which changes are necessary (and viable) and this will be debated in chapter 7.

6.10 SUMMARY

This chapter analysed the main problems associated with current BM practice and highlighted the shortcomings of existing BMSs. The discussion of the problems encountered during the implementation and operation of such tools helped shed light over user expectations and confirmed certain flaws in the architecture of existing systems. The results of the critical analysis will serve as the basis and the justification for the proposal of an innovative theoretical framework to guide the development of a new generation of advanced systems capable of overcome the problems in the next chapter. It will investigate an innovative architecture, based on the incorporation of several IT developments, and explore the idea of broadening the scope of the factors considered in the decision-making leading to the establishment of a social and holistic appraisal model. The scope of the changes is such that it will lead to the introduction of the concept of advanced systems.

Chapter 7

Outlining the Concept of Advanced Bridge Management Systems

7.1 Introduction

The critical analysis carried out in chapter 6 provided support for the argument that enhancements are necessary in the area of Bridge Management Systems. This chapter establishes the foundations for the development of a new generation of such systems. It discusses suggestions for improvement encountered in the literature and proposes a path of evolution for the development of what will be denominated Advanced Bridge Management System (ABMS). The insights gained during the critical review of limitations present in the previous chapter are used in the elaboration of a set of guidelines to help steer the future development of this kind of tool. This provides the basis for the discussion of technical and procedural changes that will define a framework for change proposed in the later parts of this chapter.

7.2 Introducing the notion of Advanced Systems

Given the momentum for change discussed in chapter 6, this thesis sustains the idea that there is a clear opportunity for the creation of new and more developed systems for Bridge Management. The pursuit of improvements in this field is important since, as pointed out by the AASHTO [1992], "the signs of a healthy organisational function such as Bridge Management is that it continually improves over time".

The challenge, as described by Shroff and Nathwani [1995], is to create a computing environment for the bridge community that will alleviate the information management burden. Several suggestions for the improvement of Bridge Management Systems are found in the literature. By combining these suggestions with the results of the critical evaluation carried out in chapter 6 and the examination of experts' opinions, the author defines a general framework for the production of a new generation of systems, which will be denominated as Advanced Bridge Management Systems (ABMS).

7.3 Strategy for Outlining a Framework for Change

The first step in the process of outlining the framework for change will involve the definition of a series of guidelines that will shape the expected behaviour of advanced systems, as discussed in section 7.4. Based on this set of guidelines, the second step will consist in the discussion of a potential set of improvements. Some of the improvements investigated are of a more structural nature and will demand the introduction of new technologies corresponding, to a certain extent, to a shift in paradigm. Other improvements will be more theoretical in nature, consisting of changes that affect the way some of the management activities are carried out, in this way refining the existing paradigms. Using this distinction, the improvements proposed are categorised in two classes, referred to as technical and procedural changes. The technical changes are the ones that will affect the architecture of the system and will be discussed in section 7.4 while the procedural changes are related to the procedures encapsulated in the analytical core and are examined in section 7.5.

Each of the two sets of changes could be seen as corresponding to the stimulation of one of the two components of an Information Management Strategy, as registered in chapter 3. Iliff [1994] remarks that different flows might predominate between these two components in different applications. In a pure bottom-up approach, the possibilities offered by IT will define how the information system will be shaped. Conversely, in the top-down approach the theoretical imperatives will determine the shape of the system. In a balanced strategy both flows must occur. This is what will be sought in the development of an ABMS. Das [1997a] emphasises the benefits of taking on board new developments, both procedural and technical, suggesting that this can lead to significant improvements.

7.4 Guidelines for the Behaviour of Advanced Systems

The development of any software should follow the generic design principles of software engineering. These include several traditional requirements such as robustness [Guida & Tasso, 1994]. This thesis considers, however, that it is necessary and feasible to draw a list of more specific design principles that a system should ideally follow to constitute an advance in terms of Bridge Management. A set of additional development principles was therefore established to help guide the transition from the actual state of development into the emergence of an Advanced Bridge Management System, as seen in figure 7.1.

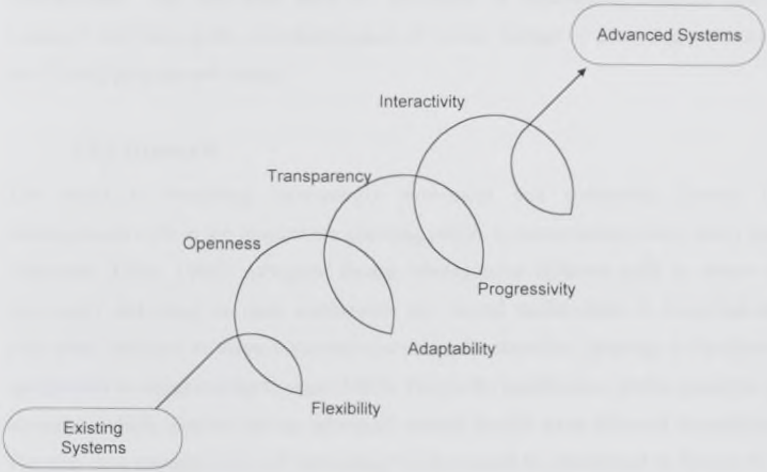

Figure 7.1 - Guidelines defining the expected behaviour of Advanced Systems.

Insights collected from the examination of bibliographic and informal sources, such as discussions held on conferences and conversations held with bridge inspectors and bridge managers, were initially used to develop this set of guidelines. The set was then submitted to the criticism of experts during the Knowledge Elicitation Exercises and considered adequate. A brief explanation of each of its component is given below.

7.4.1 Flexibility

Flexibility is the main idea from which the whole concept of advanced systems will stem. The principle of flexibility states that an advanced system should be designed having in mind that the necessities of a bridge manager are complex and dynamic. As long as feasible, no strict and rigid path of calculation should be enforced and no unique format for the presentation of results should be adopted. Instead, mechanisms should be created to allow the user greater freedom to choose the best way to use the software. Support for the adoption of this principle can be found in a report from ASHTO [1992], which states that Bridge Management Systems must give extreme consideration to the need for flexibility in decision-making and should be responsive to new inputs and circumstances. A basic requirement embodied in this principle is that the type and scope of the information produced should be open to changes trough customisation. The user must have the possibility of establishing different policy scenarios and altering the prevalent system of values instead of accepting a standard set of static policies and values.

7.4.2 Openness

The world is becoming increasingly networked and connected. Recent IT developments such as the Internet are allowing people to communicate more easily and efficiently [Grilo, 1998]. Advanced Bridge Management Systems must be aware of this reality and adopt an open architecture that would enable them to communicate with other software or share information seamlessly, therefore adopting a distributed architecture as suggested by Cooper [1997]. This is the justification for the principle of openness, which implies that an advanced system should have informal boundaries. The idea of a singular and self-containing whole should be abandoned in favour of a more modern and decentralised structure. It is expected that advanced systems will evolve towards a virtual structure, where a user-friendly co-ordinated interface hides an extensive and loose conjunction of modules with different and complementary functions (see modularity) that can even be physically located in different places.

7.4.3 Adaptability

The principle of adaptability suggests that advanced systems should always be able to make use of the existing data to produce some kind of result, no matter its precision or completeness. Distinct behaviours must have to be adopted depending on the amount and quality of data available. If detailed data is available, the software should use it to produce more precise information and deliver the best possible results. If , on the other hand, the more strict data requirements are not fulfilled, the system should still be able to produce an acceptable output, recurring to previously stored average values or "default" values or, in their absence, inferring the necessary information from the incomplete data, using sensible reasoning mechanisms.

The principle of adaptability is vital due to the high cost of producing, maintaining and updating data about a great number of bridges. Some of the enhancements in advanced systems will require great amounts of data in order to be explored to their full potential. This could constitute a very important barrier to the introduction of such tools in practice. Bridge authorities already suffer from strained human resources, as indicated in chapter 6, and the re-deployment of personnel to extensive data collection activities would probably not be welcomed. The introduction of systems that require extensive data collection before they could start to operate would therefore be compromised. It is necessary to adopt certain measures to increase the chances of success in the implementation of data intensive advanced systems. One of them is to introduce the system in operation gradually (see progressiveness). This is considered as the best strategy but will require that the software be able to make use of the available data, even if this is incomplete or out-of date, to generate approximate but useful results. As soon as new data that would refine the results is added this should be taken into account to improve the precision of the results.

A practical example of the adoption of such an approach is given by Rada et al [1993]. They used it in the development of a pavement management system for the John F. Kennedy International airport. The system algorithms were formulated based on the assumption of complete data, but they were modified during implementation to introduce a mechanism to allow the system to fall back into alternative positions in the event of some key data be missing from the database.

7.4.4 TRANSPARENCY

As discussed by Reynolds [1992], it is important to ensure that the user understands the models that compose a system, not just how to use them, but also the basic assumptions on which they are based. The principle of transparency implies that advanced systems should enable the user to verify all the assumptions adopted during processing and allow him to override them. This extended control over the computing effort can lead to a better understanding of the problems and induce a more critical view of the results, helping to avoid the pitfalls discussed in chapter 6. As seen before, computer generated results can sometimes lead to inaccurate perceptions about the precision of a result, due to the inappropriate valorisation of the computer processing effort without a critical view of the input data. One of the ways to avoid this problem is forcing the software to present the results together with observations about the limitations or adaptations adopted in the processing, so the user can have a better understanding of the uncertainties associate with the computer output. This kind of posture also facilitates the verification of how the results can be affected by a change in the conditions assumed before the analysis was carried out. Having more information about the reasons for the computer's choices of a course of action and work method can help understand how they are affected by unexpected factors. As an example, it was discussed in the flexibility principle that the user should be able to choose different policies for the maintenance of the network, since the aims of the authorities can change with time due to modification on perceptions, political influences or other factors. Therefore, the principle of transparency demands that each analysis performed by the software states clearly how the requirements associated with the policy adopted have influenced the decision-making process, modifying priorities and affecting the programming of actions.

7.4.5 Progressiveness

Because there are serious problems associated with installing a new system (resistance to innovation, training, etc.), the software design must encompass the possibility of a partial and progressive installation of its components, while preserving its capacity for delivering valid results. This is an especially important factor because some of the specific components that would probably be part of the structure of advanced systems, like congestion management modules or environmental restriction thematic maps, are not usually available for an immediate incorporation into the system. It is expected that initiatives of this nature will be develop in the next years, so the system must be able to smoothly change from a more limited and simple state to more complex ones, without demanding strenuous efforts to ensure that things are running accordingly.

7.4.6 Interactivity

The principle of interactivity was included because the author agrees with the view expressed by Martin and Powell [1992], that Management Information Systems should be an amalgam of human and computer-based activities. Therefore, man and machine should have different but complementary roles to play to achieve the successful operation of a system. The principle of interactivity states that the software design should create frequent opportunities for the user to interact with the computer, guiding the processing efforts according to the real needs of the problem and directing the establishment of solutions using engineering sense. The user is seen in this view as a moderating influence on the process. Reynolds [1992] argues that people tend to naturally favour interactive systems, but points out various problems associated with the introduction of interactivity into software design. These are mainly related with increased complexity, higher demand of computer resources and requirements and extended response time. He suggests, however, that in the majority of cases the eventual benefits can outweigh the difficulties.

7.5 Discussion of Technical Changes

As discussed in section 7.1, changes seem inevitable to bring Bridge Management in line with an increasing wired and dynamic world. One of the assumptions of this thesis is that there are various IT and AI technologies that could be useful in development a more advanced architecture for advanced Bridge Management Systems. Numerous alternatives for improvement have been suggested in the literature but the potential benefits to be accrued in adopting each of them are not accurately known. However, considering this limitation and abreast of the developments in the field of IT, a list of possible structural changes was drawn.

The various changes discussed in this section are based on harnessing the power of recent developments that have created opportunities yet largely untapped in the domain of Bridge Management. The collection of possible enhancements is considered by the author to be a fair representation of the type of change that is being advocated today in the domain of this research. They range from the development of better data storage facilities to the introduction of new and spatially oriented user interfaces. A short review of each of them is presented below.

7.5.1 Graphical Interface

One of the simplest changes identified as necessary is the improvement of the communications with the user by the adoption of a more graphical interface. The review of BMS software carried out showed that the majority of systems in operation are textual and dos-based. Immediate benefits in terms of clarity and communication with the user could be expected by adopting a windows-based interface. The most recent systems have already started to be produced with this enhancement, as seen in version 3.0 of PONTIS [Thompson, 1994] released during the evolution of this thesis.

A more radical change in terms of user interface would consist in the development of an interface referenced spatially [Itoh et al., 1997][She, 1997]. The geographical representation of concepts provides an intuitive and easy to grasp way of presenting great quantities of data [Bracken & Webster, 1992]. This technology is seen as an adequate way to provide Bridge Management Systems with an improved ability to convey the merits of bridge policies, programmes and budgets to lay audiences [AASHTO, 1992].

7.5.2 Automated Data Collection

Sabol [1995] sees automation as one of the strong trends for bridge related research. He considers that automation will probably rely in robotics for inspection as well as in the introduction of automated data collection. Advanced systems will consequently be expected to incorporate procedures to monitor and process data collected by self-monitoring and on-line sensors. Technology such as optical fibre [Measures et al., 1995] or other embedded sensors, allied with the expansion of the means of communication might allow future systems to continuously monitor the evolution of the conditions of a structure remotely almost without human interference. This could provide abundant and precise data for the development of deterioration models while at the same time supporting the creation of more sophisticated reasoning routines based on the increased sensorial capability of the systems.

Real time monitoring techniques based on the establishment of a closer interaction between vehicle and the road might also play an important role in the future, contributing to increase the amount and quality of the data available for analysis while providing mechanisms to manage the impacts of bridge deterioration and maintenance. In the UK the government has been looking into several telematic applications including automatic incident detection; in-vehicle congestion information; electronic maps; autonomous route guidance and autonomous intelligent cruise control [DTER, 1996].

7.5.3 Multimedia Storage of Data

A widespread suggestion for improving Bridge Management Systems consists in the adoption of multimedia oriented databases to support systems capable of manipulating non-textual information content [Das, 1997a]. Deighton and Lee [1993] enumerate eight possible types of data: alphanumeric, spatial, graphical, image, document, audio, video and time. Advanced systems will be expected to deal with all, or nearly all, these formats. The software IBIIS (Integrated Bridge Inspection Information System) could be appointed as a suitable example of such a tool [Shroff & Nathwani, 1995]. Lauzon and Sime [1993] exemplify the benefits of this kind of approach by describing the introduction laser videodisk technology to store photographic logs of pavement sections and bridges in the Connecticut BMS (CBMIS). The system was a simple First Generation tool but just the use of video storage was already able to enhance the work by facilitating identification and improving communication.

7.5.4 Distributed Resources

The adoption of adequate mechanisms to control the access and sharing of the data and information stored is a major factor in the development of a reliable system. In earlier Bridge Management Systems, this was taken as an expression of the need for establishing a centralised database, measure that was frequently beneficial if well-structured database structures were developed. For example, the establishment of a single central database during the development of the Connecticut system referred before was attributed to have increased productivity by reducing and optimising the flow and distribution of information between the various sectors acting on bridge maintenance, solve "some vexing operational problems" [Lauzon & Sime, 1993]. Despite the fact that it helps reduce data redundancy, the idea of a single database has started to be reviewed more recently. According to Shroff and Nathwani [1995], there is a requirement for speeding the flow of information in the bridge management process and enhance the access to data at all points. To achieve this it is necessary to allocate the responsibility of managing and maintaining information to the parts most able to do it. Instead of concentrating information, it is considered more vital today to create mechanisms to allow a reliable flow of information between different parts of the system, decentralising the administration of data. This prompted the idea of adopting a distributed database structure for advanced systems. This approach avoids putting the burden for collecting and managing the information in just one body.

Database elements might be physically located in different places but, provided that a sound management scheme is adopted, the information flow occurs seamlessly.

7.5.5 Geo Referencing

According to Longley and Clarke [1995] the use of geography, i.e. the geo-referencing of data to support spatial analysis, is one of the keys to enhance Management Information Systems (MIS). The author agrees with the concept and argues that many of the analyses involved in the assessment of the impacts of maintenance are based on the use of geographical operators and they could only be done adequately using a geographical interface. The AASHTO [1992] supports this view and suggests that the dissemination of desktop tools with GIS capabilities can provide a very interesting platform to analyse and display maintenance options, decisions and outcomes.

Another important reason behind the suggestion of adopting geo-referencing is related to the trend towards the integration of systems, discussed in chapter 3. The integration with other ISTEA mandated systems is considered as a logical and necessary step in the evolution of Bridge Management Systems [Chase, 1995]. The trend should be recognised by advanced systems and this must prompt certain changes in their architecture to facilitate integration. . A common structure of data storage and a single interface must be provided. An important change would be the adoption of a common interface for the various highway infrastructure systems and geo-referencing provides the tools for this.

7.5.6 Use of 3D models or Virtual Reality

The improvement of data visualisation was also carefully thought about as a possible alternative for improving existing systems, since studies [UMIST, 1997] have shown that this is considered as one of the areas with most promise in terms of potential improvement brought by the use of IT in construction. There are various techniques being discussed for improving data visualisation and manipulation in the literature. Gomez-Rivas and Lopez [1997] advocate the use of 3D models instead of paper drawings arguing that these models facilitate the communication between the professionals involved in bridge inspection and repair. Fischer [1997] discusses the advantages of animating 3D models according to a given construction schedule to create 4D models. He argues that these multi-dimension environments are the most effective tools to allow the co-ordination of design activities. Closely associated with 3D/4D modelling is Virtual Reality representation. Oliveira [1998] defends the use of VR based on the familiarity of people with 3D environments and taking into consideration the possibility of performing tasks in real time. According to him, this approach could allow the creation of an accurate representation of the structure that could then be analysed and manipulated in a virtual environment. It could further allow the introduction of accurate simulated training routines for experts.

7.5.7 Object Orientation

One fundamental change considered for the improvement of the architecture of advanced systems is the use of object orientation to guide the segmentation of the software in self-containing "modules". It is considered that the appropriate use of the concept of object modularity could introduce a considerable degree of simplicity and clarity on the design of ABMS. It would also put advanced systems in line with the trend towards software interoperation discussed by Cooper [1997].

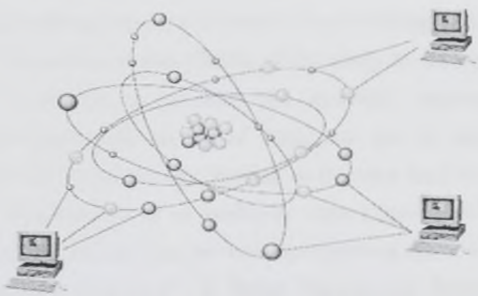

Figure 7.2 – Model of a distributed object approach [Cooper, 1997].

The dissemination of object orientation would mean that it would be possible for a system to access individual components of another existing system. New applications could then create and manipulate instances of objects put at the general disposal by existing applications. Each software component would be seen as a provider of services not just to other components in the same application but to all applications that need it, as suggested in figure 7.2.

7.5.8 Soft Reasoning

Soft Computing is an emerging approach to computing which aims to emulate the remarkable ability of the human mind to learn and reason in an environment of uncertainty and imprecision [Zadeh, 1992]. According to Jang et al. [1997], it is an innovative approach to construct computationally intelligent systems. This is seen as a very promising area for the enhancement of decision support systems such as Bridge Management Systems. Soft reasoning is usually based on the use of some kind of knowledge based reasoning technique. The "Bridging the Gap" report produced inside the Construct IT initiative in the UK [BT & Department of the Environment, 1995] considered that improving the analysis process though more extensive use of knowledge based engineering is a major opportunity for improvement in the domain of construction.

There are two main objectives envisioned for the incorporation of KBS components in advanced systems: the introduction of a support for approximate reasoning and the development of a capacity for learning. Approximate reasoning plays a basic role in human decision-making because it provides a way of dealing with problems which are too complex for precise solution [Zadeh, 1975]. Using AI techniques of approximate reasoning it is possible to reproduce this capability. Approximate reasoning is commonly associated with the use of fuzzy sets and the adoption of linguistic variables. The capacity to simulate learning on the other hand is arguably one of the most crucial characteristics of an intelligent entity [Cawsey, 1998]. Watson [1997] considers the ability to learn from previous experiences as one of the key features of an "intelligent system component". If Bridge Management Systems are to become intelligent assistants it will be necessary for them to incorporate this capacity to some degree. Case based reasoning (CBR) is considered as the best approach to model the learning mechanism [Oliveira, 1998].

7.6 Discussion of Procedural Changes

Beyond the enhancements in the architecture discussed in the previous section, modifications in the routines encapsulated in the analytical core of Bridge Management Systems are also increasingly becoming necessary, as discussed in chapter 6. To create advanced systems it will be necessary to identify and implement better ways to undertake some of the critical tasks normally involved in the process of managing bridge maintenance and repair. The analytical core contains the majority of the value adding functions in terms of information processing [Bracken & Webster, 1992] and the discussion will focus in this area.

Many ways have been discussed in the literature to improve the analytical capabilities of existing systems. Researchers in England have been particularly interested in the topic since, as reported by Das [1997d], a series of studies have been dedicated in the last few years to define the best format for a new comprehensive Bridge Management System for the Highways Agency. Thoft-Christensen et al. [1996] commissioned discusses the combination of structural and economic factors under a probabilistic framework for assessing the risks and determining the best time for maintenance of bridges, an area that is also being investigated by Burdekin [1998]. Blakelock et al. [1998] have meanwhile been involved in the creation of a new condition index.

In other countries the interest has also been great. Vesikari [1992] has studied the possibility of developing defect specific Transition Probabilities while other research was directed at the evaluation of traffic impacts of intervention [Cassidy et al., 1993] and decision-making procedures [Madanat, 1993]. Suggestions for improvement involve the development of procedures to automatically determine the need for and schedule inspections with some authors [Frangopol, 1997] even suggesting the use of the information about the condition of the bridges and the potential risk to define variable intervals for inspections

Having reviewed a great number of these developments, the main procedural changes that could bring benefits for an advanced system were identified by the author as including:

- the development of inspection expert modules based on KBS technology;
- the introduction of the concept of defects for condition assessment;
- the correlation between risk and condition state;
- the development of more accurate techniques for deterioration forecast;
- the widening of the scope of the economic appraisal;
- the development of modules for assessing the condition state and forecast needs.

7.7 Establishment of a Generic Outline of an Advanced System

Having defined the guidelines for the behaviour of an improved Bridge Management System and discussed the most relevant technical and procedural changes advocated in the literature or identified as necessary along this work, it is now possible to consolidate what would constitute an advanced system. It is adequate to recognise that a great deal of development has already occurred in this area, as demonstrated by the analysis of the typology of existing BMSs carried out in chapter 3. Table 7.1 identifies the main characteristics that define each of the generations developed until today and suggests what, in the view of the author, would be the main characteristics that would distinguish advanced systems from current systems.

Table 7.1 – List of the main features of existing Bridge Management Systems and of the extensions envisioned for Advanced Bridge Management Systems.

Description	Data Storage	Analytical	Decision Support	Advanced
Generation	First	Second	Third	Fourth
Data Storage/ Retrieval	X	X	X	X
Condition Assessment		X	X	X
Ranking		X	X	X
Condition Forecast			X	X
Network Analysis			X	X
Cost/Benefit Analysis			X	X
Open Architecture				X
User Oriented Interface				X
Spatial Integration with Infrastructure Systems				X
Distributed Structure				X
Social Perspective				X
Hybridisation				X
Multi-Reasoning				X
Polymorphism				X

Each of these innovative characteristics is briefly described below and the connection between them and the technical and procedural changes proposed before are clarified.

Open Architecture

The combination of distributed databases with object orientation and the adherence to the principle of flexibility will lead to the development of a open architecture is advanced systems. An advanced system will be developed as a loose association of independent objects, as suggested in figure 7.3 and should be able to relate to different elements and databases distributed over an intranet, a dedicated connection or even over the internet.

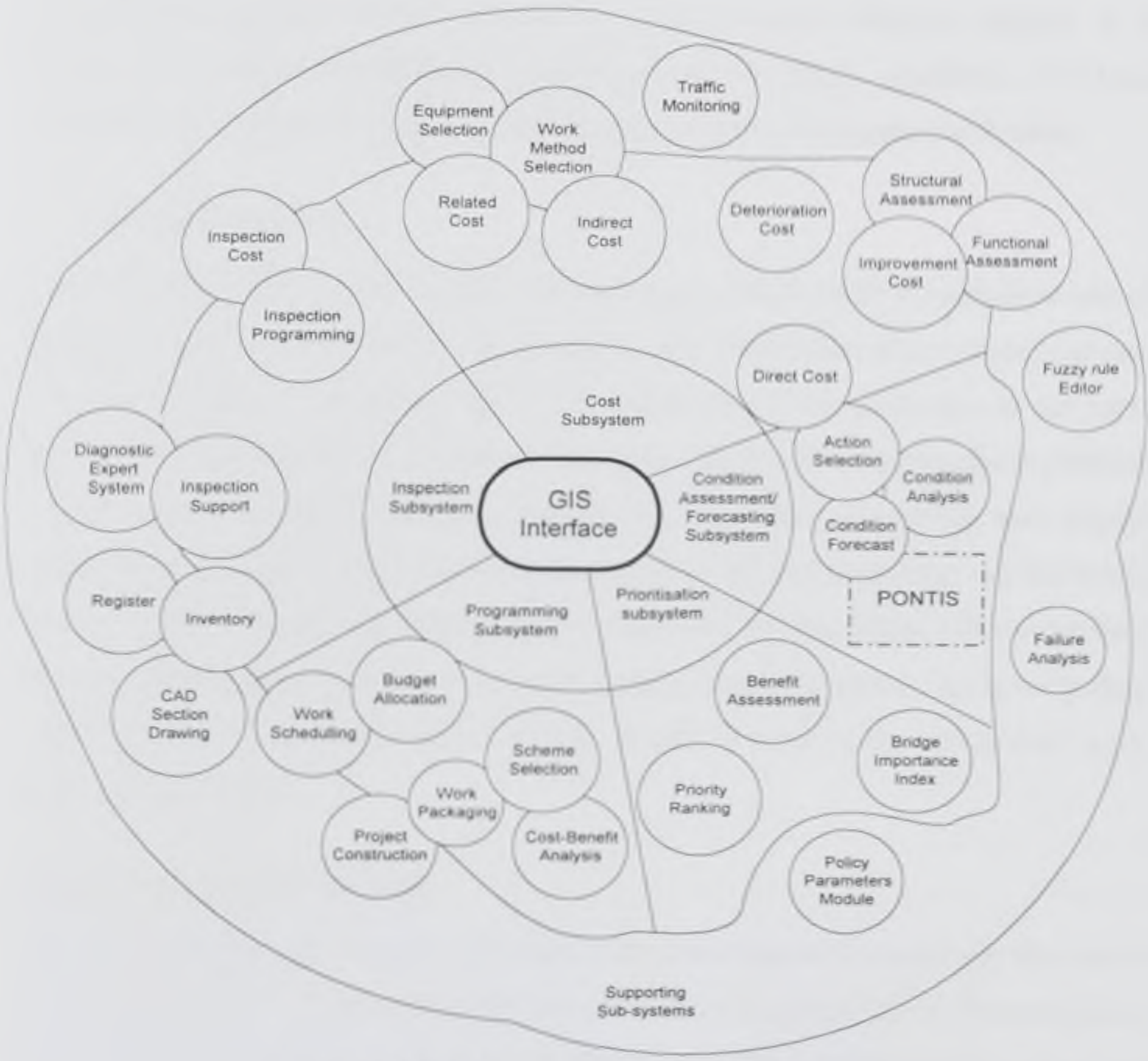

Figure 7.3 – Illustration of Open Architecture.

Some of the existing Bridge Management Systems already use modularization, but it is the view of this thesis that this characteristic should be pushed to the centre of the architecture of new systems. Advanced systems should be divided into modules that perform specialised functions and that could be combined in various ways to produce different results.

The adoption of an open architecture can have considerable results in terms of implementing the principle of flexibility, since the system could switch modules on and off, depending on the needs and interests of the current user. Additionally, the use of object orientation would mean that improvements on any of the different knowledge areas embodied on the system could be introduced simply by substituting the existing object with a new one, providing that certain basic data storage rules are followed to ensure good communication with the rest of the system. This would help allay fears expressed by some experts that new theoretical developments could render their management programs obsolete because it would demand laborious updates. It is important to highlight nonetheless that the adoption of object orientation will have impacts in the way data is organised and shared in a Bridge Management System.

User Oriented Interface

The creation of effective and natural ways to interact with the user is considered one of the main objectives that needs to be pursued in the production of advanced systems. The use of graphical interfaces will be the initial step in this direction. At the same time, the use of digital maps and geo-referencing can provide a more natural platform for the analysis of bridge networks. Finally, the capability of working with natural language statements introduced by the incorporation of soft reasoning can flexibilise the way computers deal with information. Systems will be able to deal with uncertainty by using approximate reasoning to consider perceptions and opinions. In this way they would be able to suggest possible courses of action even in the absence of more detailed information.

Adoption of a Social Perspective

Other important change considered as necessary (see chapter 4) consists in the use of more comprehensive criteria for the definition of MRI strategies. Even if cost is taken as the main driving factor, they must be balanced against a wider social view of the problem, in a way that other non-monetary costs are also included. The emergence of the Value for Money policy gives evidence to this fact. In accordance with this suggestions an advanced system will be expected to be able of considering the problem of establishing MRI strategies from a true social point of view. To achieve this end the concept of bridge utility will be used as a holistic measure of investment worthiness considering the effects in all parties of society and the environment.

Integration

Due to the use of geo-referencing, it is expected that advanced systems will be able to integrate with other systems, as suggested in figure 7.4. This is an important feature since it is considered necessary on the long run to understand BMS as just one part of a larger structure designed to integrate all parts of infrastructure management. The choice of MRI interventions in bridge should reflect the set of priorities determined by an articulated infrastructure management strategy.

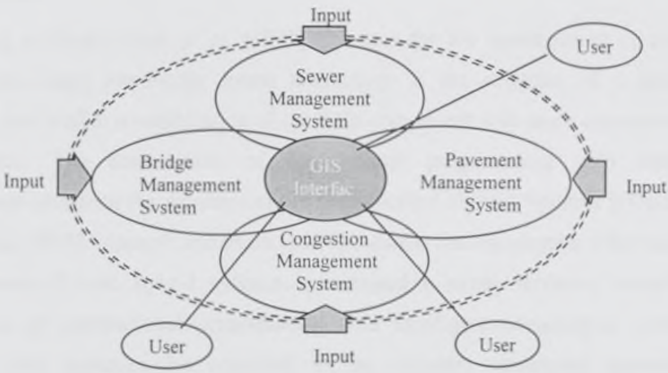

Figure 7.4 – Representation of the concept of integration of Infrastructure Systems.

Distributed Structure

The use of a distributed architecture is in line with recent developments in communications technology [Grilo, 1998] and could be a critical factor in organising and managing the great amount of data necessary for Bridge Management. Databases could be stored on different machines, over an Intranet or even on different networks. Internet access could be provided and hypertext links built inside the management system to establish on-line connections with the data or information necessary. Searches and retrieval algorithms could be use to gather specific data from suppliers or other external sources, such as traffic management information systems. Special attention should be given to prevention measures to avoid corruption of databases. Security copies, limited access clauses and other mechanisms should be incorporated in the design to minimise this risk. The envisioned architecture includes the use of several local or secondary databases that would contain thematic or limited sets of detailed data to be used in the bulk of the calculations. Just the main information necessary for network optimisations would be stored in a leaner database under the administration of a central authority in charge of money distribution. This primary database would mainly be used to support exploratory analysis aimed at identifying tendencies of average behaviour over the entire network. They would also provide subsidy for money allocation exercises that would take into consideration the broader picture about deterioration trends and maintenance needs.

Hybridization

According to Harris-Jones at al. [1992], the key for the development of practical applications using knowledge based technology is the adoption of a integrated approach that lead to a combination of the KBS component with more conventional IT components. The combination of conventional programming with intelligent components results in the development of the so-called Hybrid Systems [Goonatilake & Khebbal, 1995]. Aamodt and Plaza [1994] consider that the success achieved in the development of such hybrid systems has created a strong tendency towards the integration of conventional programming with intelligent components. Advanced systems will therefore be expected to be hybrids, combining conventional programming techniques with knowledge-based reasoning or other AI techniques.

Multi-Reasoning

According to Guida and Tasso [1994], the option for a hybrid architecture instead of a pure conventional programming method reflects a widening of the focus of attention from algorithm design to include the representation of the knowledge considered relevant to the solution of the problem. Soft computing is usually associated with the use of some kind of knowledge-based system. As explained by Fengeibaum [1991], a system is considered to exhibit "intelligence" due to the specific knowledge that it contains about the problem domain. The intelligent component is an additional tool to help solve a particular class of problems in the application domain or give additional capabilities to the system. The combination of conventional programming with some intelligent component to support soft reasoning already define advanced systems as hybrid systems. It is advocated that this hybridisation can be taken further and multi-reasoning systems can be created.

Since each reasoning technique has positive and negative points, more than one could be combined various soft reasoning techniques could be combined to achieve the expected result, in a second level of hybridisation marked by the use of different methods to fulfil specific and complementary roles in a system. This is the architecture advocated for advanced Bridge Management Systems. The association of CBR and Fuzzy components is seen as especially interesting because they complement each other. The CBR component could be used to make a initial screening and avoid the need for the reasoning if very similar cases were identified. Modules using case-based reasoning or similar technologies could also be designed to take into account the reaction of the user to actions recommended or suggestions made by the computer. The system could use this information as an extra factor to judge the appropriateness of future choices, in this way simulating a learning capacity.

Intelligence

As discussed in chapter 3, Third Generation Bridge Management Systems can be considered as decision-support tools. According to Bracken and Webster [1990], this would imply that they are a part of an integrated man/machine decision-making process but according to them the ability of the computer to participate in this interaction can vary significantly. Many of the existing systems produce good results but they are too dependent on the input of precise data to make the system behave in an adequate way. Some references suggest that it is necessary to give the computer a more "intelligent" role. The author defends the idea that an advanced system should try to reproduce the human capacity of making sense of imprecise and complex situation while maintaining the innate ability of computers to deal with a great number of data at the same time.

Subscribing to this idea, this thesis advocates the notion that advanced systems should become effective "intelligent assistants". These more sophisticated tools should be able to deal with situations where just uncertain or incomplete data is available and use the experience accumulated and common sense reasoning to develop solutions to new situations, helping to solve some of the difficult problems that are very common in Bridge Management. The use of soft reasoning will allow the introduction of this "intelligence". The introduction of soft reasoning denotes additionally a capability of dealing with natural language which is considered by Watson [1997] as one of the most significant features that characterise "intelligent systems".

Polymorphism

Because the incorporation of soft reasoning techniques supports approximate reasoning does not imply that users will not prefer more precise calculations if enough data is available. A multilevel reasoning architecture is therefore advocated for advanced systems. This implies that an advanced system should have the capability of adopting different behaviours depending on the amount of data available for the calculations.

The polymorphism of advanced systems would be expressed in practice by the use of different sequences of operations, by the activation of different methods or classes and by the adoption of standard values instead of calculated ones. The idea is that the systems should use the best information possible but recur to less precise information to be able to produce an answer in a great number of cases, even if it can just produce an approximate result.

At least four levels of operation are envisioned for an advanced system, as described in figure 7.5. The User can define which one he would prefer.

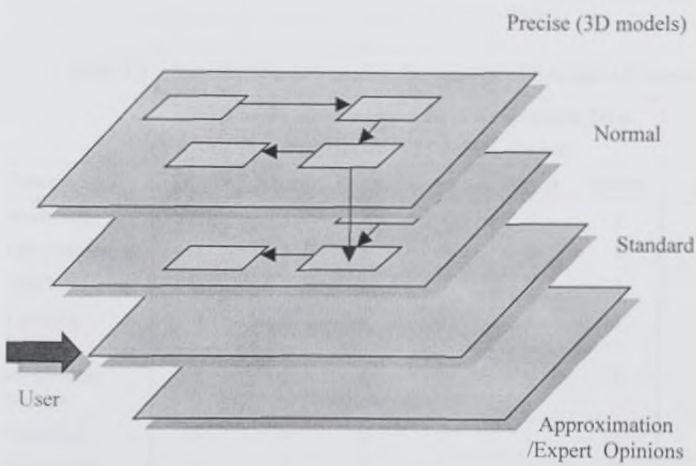

Figure 7.5 – Illustration of polymorphism in an Advanced System.

7.8 Selection of Changes to Investigate in this Thesis

It was impossible to develop all the changes described before and therefore it was necessary to select the ones that would be of greater impact in the short term.

7.8.1 Changes in System Architecture

A two-phase strategy was established to define which technical improvements should be pursued in this thesis. The first step was to analyse how each of the possible changes advocated before would correlate with the design principles established in section 7.3. The results are summarised in table 7.2.

The table shows that the use of a graphical interface will benefit the transparency and interactivity of the software. On-line data collection would probably add flexibility. The distributed databases facilitate openness and interactivity, since people can have more control on the data concerning their activities. Multimedia storage would mainly impact interactivity, but would also improve interactivity because richer information can be presented to the user, helping him understand the problem better. Modularity is considered to have a great impact in the majority of principles, except interactivity.

Table 7.2 – New features included in the concept of Advanced Systems.

	Effect on the achievement of the design principle listed (0- nothing 1- little 2 - medium 3-great)						
Description	Flexib.	Open.	Adapt.	Transp.	Progres.	Interac.	Score
Modularity	3	3	2	1	3	0	12
Geo-referencing	1	3	1	3	0	2	10
Soft Reasoning	1	0	3	1	0	3	8
Learning Capacity	2	0	1	1	1	3	8
Multimedia Storage	1	1	1	1	0	3	7
Graphical	0	0	0	2	1	3	6
Distributed Databases	1	2	1	1	1	0	6
3D Modelling / Virtual Reality	3	2	0	0	0	0	5
On-Line Monitoring	2	1	1	0	0	0	4

Hybridisation will be the major support for adaptability and the use of natural language will be an important element of interactivity.

The various changes were then subject to the scrutiny of experts to help determine their potential for improving the architecture of BMSs. The results are shown in Figure 7.6, where the scores given by the experts are aggregated. Since the individual grades could vary between 0 and 10 and the number of experts interviewed was 10, the aggregated totals varied between 0 and 100. All techniques that received an aggregated approval rate of more than 2/3 (66) were considered as primary candidates to be implemented. The use of a graphical interface, modularization and geo-referencing were enthusiastically supported. Multimedia storage also received plenty of support.

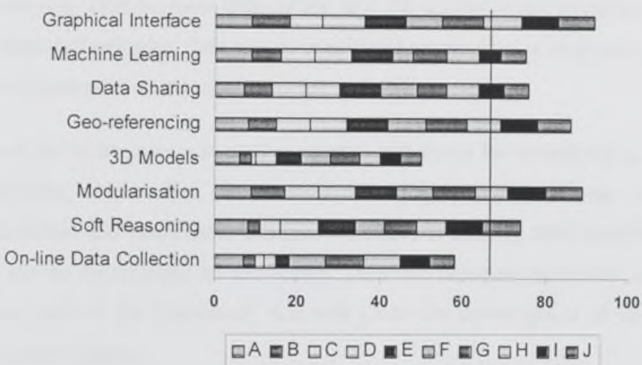

Figure 7.6 - Expert assessment of the suitability of various proposed changes.

Two techniques fell behind the designated threshold of approval: 3D modelling and on-line Data Collection. The explanation for this might be found in the concern expressed by the practitioners about the impact on the workforce of changes in procedures introduced by the adoption of such techniques. They believe that there is room for improvement, but because new techniques are based largely in the use of more data, they are afraid of creating extra demands that could not be attended by their already scarce workforce.

Automated data collection techniques could help produce more accurate data that would allow the computer to make a real-time assessment of road usage and be adjust decisions for incident occurrence, facilitating the analysis of the impact of maintenance and improving the quality of the control of bridgeworks. However, the cost and the technical difficulties in of implementing them are a major barrier to their dissemination. It would also be necessary to create special mechanisms to monitor and process all the data being collected. Intelligent filters and data aggregators would probably be necessary. The experts also considered the use of 3D models and virtual reality as not adequate. The validity of such concerns was confirmed by a short study to evaluate these techniques carried out at UMIST with the participation of the author, which showed that the amount of data necessary for such an undertaking would be significant. This would probably make the introduction of such technology difficult in authorities that are already struggling with reduced human resources to carry out traditional bridge inspection and repair. This was the reason why it was excluded from further analysis. Due to these difficulties and the unfavourable opinion of experts towards these technologies, they will be considered promising but long-term objectives inn the evolution path of advanced systems.

The rest of the techniques was well supported and could be considered as ready for implementation. Nonetheless, the introduction of graphical interfaces, multimedia storage facilities and distributed database structures is already well-established areas and will not be investigated in this thesis. They are however implicitly assumed as constituent parts of the framework that will guide the development of an advanced system in later chapters.

Considering the abidance to the design principles, the opinions expressed in the literature and the convictions of the experts the technical changes selected to outline the improved architecture of the advanced system to be developed in this thesis will incorporate the following changes:

geo-referencing,

modularization and

soft reasoning based on the use of fuzzy logic.

This set changes is considered innovative enough to ensure that the system developed will incorporate enough differences to warrant its classification in a new generation of Bridge Management Systems.

7.8.2 Changes in the Analytical Core

The problems with existing condition forecasting procedures were highlighted in chapter 6 and are the main justification behind the suggestion that an advanced system should register and grade individual defects instead of just annotating the general condition of the element discussed before. However, considering that a lot of research is already being dedicated to the study of deterioration forecasting using probabilistic or deterministic methods and that:

a) the decision-making step is the one where the most important management activities are carried out (chapter 2)

b) Bridge Management Systems are essentiality decision support tools (chapter 3)

c) Value for Money is a increasingly accepted policy for Public Investment Appraisal but there is not yet a clear definition of Maintenance value (chapter 4)

d) Economic analysis is the focus of the DM process (chapter 4).

e) Economic analyses needed to subsidise a social appraisal of MRI strategies must be more far reaching than the one undertake in existing systems (chapter 4).

f) The preferred technique for economic analysis is Benefit-Cost ratio (chapter 5)

g) The scope of costs associated with a maintenance operation or the deterioration of a bridge is much more ample and has much wider consequences than just the monetary cost of the repair and the user cost (Chapter 5).

The author concluded that the investigation of an improved appraisal model should constitute the major interest of this work. The original bias towards focusing the research in structural items with less attention paid to the economic and social impacts of MRI operations has started to be reversed in recent years. Bridge Management has been recognised as a strategically important exercise to allow the better use of the road infrastructure and there is a need to strengthen the theoretical basis of the decision-making procedures involved to allow BMS to fulfil their purposes. This will be the main focus of the second parts of this thesis. The improved architecture will be used to support the new appraisal model, adding new capabilities that will be vital to allow the broadening of the scope of impacts considered.

7.9 SUMMARY

The concept of Advanced Bridge Management Systems (ABMS) was introduced and clarified in this chapter. A set of design guidelines was draft to guide the development of such tools and a series of enhancements to their structure and contents were discussed. It was defined that advanced systems should incorporate changes in their architecture as well as in the procedures encapsulated in them. In terms of system architecture, Fourth Generation systems will be marked by a high degree of modularity achieved trough object orientation that will facilitate the integration with other systems and add flexibility. The use of a graphical interface with geo-referencing capabilities will meanwhile facilitate the communication with the user, allow the spatial analysis of data and provide a basis for the creation of integrated tools for infrastructure management. Additionally, advanced systems will have soft reasoning capabilities to allow them to act as "intelligent" decision assistants. The most significant change in terms of BM practice will consist in the adoption of novel appraisal procedures based on the concepts of value and utility discussed in chapter 4. By improving the way that costs and benefits are assess and considered, the new appraisal models is expected to give more flexibility, improve the accuracy of the results. By considering the whole range of impacts, it will allow the adoption of a holistic approach to decision-making, bringing advanced systems in tune with changes in society's perceptions of transport priorities. Chapters 8 and 9 will explore and refine these changes.

Technical Changes Proposed to Produce an Innovative Architecture for Advanced Systems

8.1 Introduction

The present chapter starts to refine the framework for improving Bridge Management Systems outlined in chapter 7, discussing how to effect some of the technical changes deemed adequate. It explores how the selected IT and AI techniques will be used to support the implementation of an innovative architecture for advanced systems. The analysis will demonstrate how the combination of object orientation with a GIS component capable of spatial analysis and the use of fuzzy logic will provide systems with new and more sophisticated capabilities that can help improve their performance.

8.2 Implementing Object Orientation

The fist technical change being investigated involves the use of Object Orientation (OO) to produce an explicit modular structure. As remarked by Hopgood [1993], an object model is a very natural way of representing real world problems within the confines of a computer. As pointed out by McKelvy et al [1997], the notion of objects has developed into a very popular concept and is becoming a fundamental structure for data representation. The concept of objects is today used in a great number of systems, because it offers the possibility of creating flexible and robust applications [Meyer, 1997].

8.2.1 Background

An "object" can be seen as a virtual representation of a logical entity. To introduce this concept in a system it is necessary to segment and compartmentalise it using a new logic. Classes are *object definitions* that can be used as a blueprint for the creation of *instances* of a particular object at any point of the analysis. The object definition includes a number of slots that are used to describe the most relevant characteristics of the entity being represented. These are usually denominated as the *properties* of the object. It may also contain a number of embedded sub-routines of functions that are used to perform certain actions. These are known as the objects' *methods*.

The concept of objects implies three basic properties: encapsulation, inheritance and polymorphism [McKelvy et al, 1997]. *Encapsulation* means that all properties and methods are contained in the generic definition of an object and that an object can therefore be seen as a self-contained programming unit. Methods and attributes can be defined as private if necessary, impeding access to them from other objects and increasing robustness in some cases. *Inheritance* means that new objects can be created based on the definition of a previously existing object. The new object will automatically inherit the properties and methods of the initial object, unless defined otherwise by the programmer. This creates a natural hierarchy of objects. If multiple inheritance is allowed, the hierarchy can turn into a network of dependency relationships. Finally, *polymorphism* means that the same method call can have more than one meaning depending on the object being activated. The meaning is interpreted at run-time, using dynamic or late binding, as explained by Hopgood [1993]. This means that different objects can have distinct definitions to the same method without creating interpretation problems during compilation, adding uniformity and clarity to a system developed using OOP.

Based on the examination of various works on the subject [Gunter & Mitchell, 1994] [Khoshafian & Abnous, 1995] [Meyer, 1997], this thesis sustains the idea that the use of object orientation will help improve the organisation and facilitate the co-ordination between the various components of an advanced system. The sub-division or compartmentalisation of pieces of a program into specialised modules is not a new thing. For many years programming methods have advanced in this direction, with the use of sub-routines and functions. PONTIS itself was developed using an OOP language and is organised as individual programs that perform specific tasks [Golabi et Al, 1993]. But just modularity does not equal object orientation. It is necessary to establish a clear and organised object structure and allow the user to interact with the objects in a more direct way to achieve the objective of having a proper object model. The new structure being proposed distinguishes itself from previous initiatives by letting the various modules be more transparent to the user and by establishing a less rigid connection between them. Instead of following a determined sequence, modules are activated depending on the task being pursued, fostering a larger degree of encapsulation. This is expected to result in the equivalent of a "white-box" structure for advanced systems, addressing some of the problems discussed in chapter 6.

8.2.2 Description of the Proposed Use in an Advanced System

Two basic types of object are proposed for modelling Advanced Bridge Management Systems. These two types will be designated in this work as data-bound and procedural objects. The *data-bounded objects (DOs)* will be used to store the basic or transient information about the various "entities" being considered, such as bridges, bridge elements, access equipment and maintenance activities. Each instance of these objects will be filled with data that represent the characteristics of an individual logical entity. Because they represent different entities the properties of each DOs are naturally expected to vary. A *Bridge* object will have properties that represent the relevant characteristics of a real bridge, such as route carried, height, etc. Meanwhile, an *Equipment* object will have properties that define the type and the characteristics of the maintenance equipment available. Appendix IV contains a description of the properties of the DOs proposed in this thesis.

Since all DOs have a similar role and taking into account the principle of clarity, it was decided that, as much as possible, they should have a common structure with similarly named methods. Table 8.1 shows some details of this structure. Each DO will have a method called *Init* to prepare it for connecting to the database(s) containing the relevant data. The *LoadData* method will direct the retrieval of data and its association with the properties of the object while the *ShowData* method will control how the contents of the object can be exposed to the user for evaluation or modification. In the eventual case of changes being made to the object's properties, a *SaveData* method is charged with storing the modified values in the database.

Table 8.1 – Description of some common methods that compose data-bounded objects.

Standard Methods	Definition
Init	Initialisation routine
LoadData	Routine for the retrieval of data
ShowData	Visualisation routine
SaveData	Routine for transferring data to the database

While DOs are used to store and organise data, *procedural objects (POs)* encapsulate the various calculations necessary to support the decision-making activities. POs request data from active instances of the data-bounded objects, process this data and produce secondary data. This can in turn be used in further calculations, be presented to the user for criticism or eventually stored in the database for future reference. Because each PO has a different function, their methods are varied and no unique classification of their structure is possible. However, all incorporate the *AutoRun* method, which makes the object perform its function using values from current data objects, standard stored values or deduced values, without interaction with the user.

During the development of the object model the need for some special objects also became evident. The first special object considered necessary was called *Main Interface Object (MIO)*. This could be seen as a meta-object representing the whole analysis and that was in charge of co-ordinating the interaction with the user, controlling the creation of the main data objects and manage the activation order of the procedural subjects.

Figure 8.1 shows a generic example of how the object structure being proposed would work. When a Main Interface object denominated M is activated, it automatically creates instances of the data objects X, Y and Z, based on the information contained in the respective databases (the user can change the content of these objects at any moment if desired). The MIO then activates the procedural objects A and B and passes to them pointers to the data objects, allowing them to retrieve the data necessary to perform their operations. These objects activate secondary POs if necessary. For example, object B reads data from the images of X and Z and activates C, D and E to obtain additional information necessary to support his internal calculations. Secondary objects can serve more than one primary object, as seen in the case of object C. They can also access, and if necessary modify, the images of active data objects.

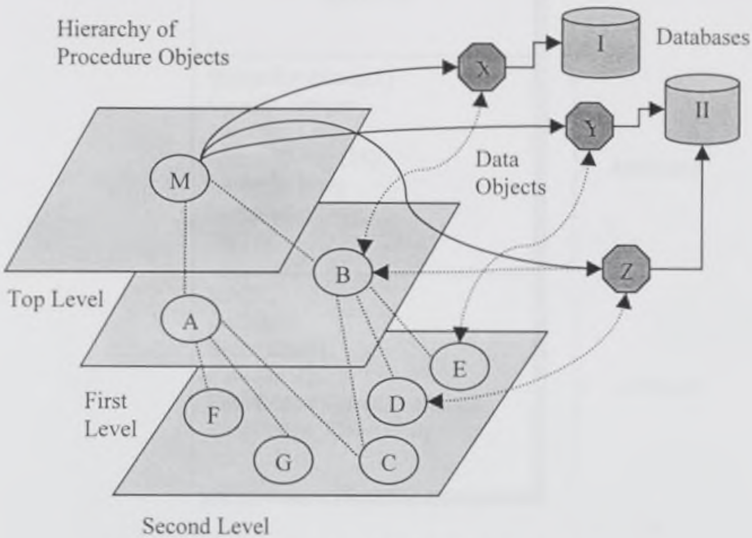

Figure 8.1 – Representation of the object structure proposed.

Changes can easily be implemented using this architecture. Due to the open nature of the relationships established, individual objects or connected groups of objects could be replaced without problems to the rest of the software. For example, object D could be replaced by an object D* in a straight swap. Or object A could be replaced by a new object A* that would not need object C anymore, instead relying on data supplied by a new object H, which would be introduced specially for this purpose and that could use some of the data already contained in Z.

There are various schemes of representations for objects. One of the most used is the Object Modelling Technique (OMT) [Rumbaugh et al., 1991]. It suggests the construction of a model to describe the structure of the objects in a system, i.e., their identity, relationships and attributes. This would provide a framework for the creation of dynamic and functional models describing how these objects would work together. Elements of this methodology will be used to create the object model for the present work. However, since the objective of the work is not the development of the model but an analysis of its impact in the development of Advanced Bridge Management

Systems, a less formal approach will be adopted. Figure 8.2 shows an example of how an object can be represented using the OMT notation.

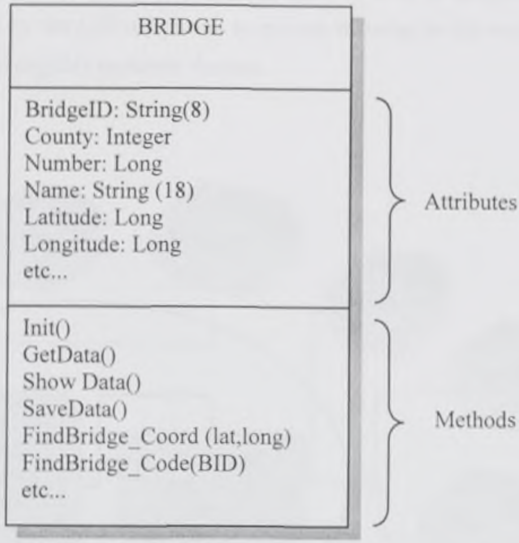

Figure 8.2 – Standard representation of an Object Class to be adopted in the work.

8.2.3 Example of Use

This thesis aims to demonstrate how the concept of objects will be used to create a innovative architecture for advanced systems. To achieve this objective a general object model with various different elements will be proposed in chapter 10. At this point, however, a particular component of this large structure will be examined in more detail to demonstrate how objects are expected to work. Figure 8.3 shows the Equipment Selection Procedural Object, which is in charge of determining which is the most probable equipment that would be used to perform a certain maintenance activity in a particular element of a bridge. As shown in the figure, two objects compose the domain. They could be further split or fused, if desired. The main object receives as input the object images of the maintenance activity (Ax) and the element (Ey) being considered. It then accesses data about the bridge to which the element belongs. Having this data, it proceeds to determine how each type of equipment would perform. To this end it initiates an equipment object, loads it with the data pertaining to that equipment and activates another PO, the Equipment Adequacy, to check the adequacy of that particular equipment. This element will in turn use data from other data objects (policy and traffic conditions) in conjunction with the results of an analysis of noise sensibility carried out by the GIS component to provide material for the evaluation of the series of rules affecting this particular domain.

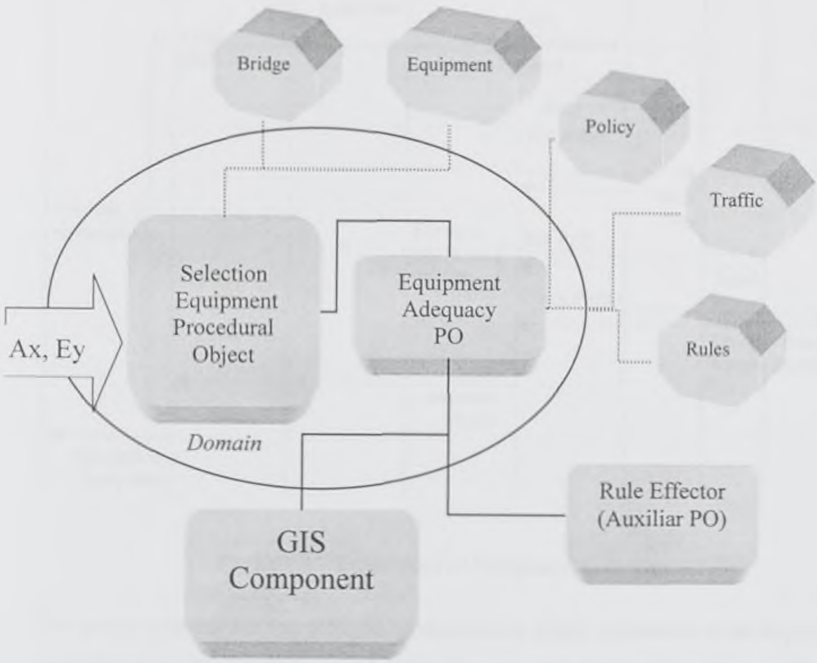

Figure 8.3 – Object Model of the Equipment Selection Sub-System.

Figure 8.4 shows an event trace diagram used to keep track of this series of events. In the figure the Procedural Objects are represented as normal rectangles while the Data Objects are representing as rounded rectangles. A generic external process was used as the activator of the Equipment Selection object. Using object orientation, an object model and dynamic models such as the event trace diagram it is possible to keep track of how individual components of the advanced system are related and how to introduce changes without causing problems to the remaining parts.

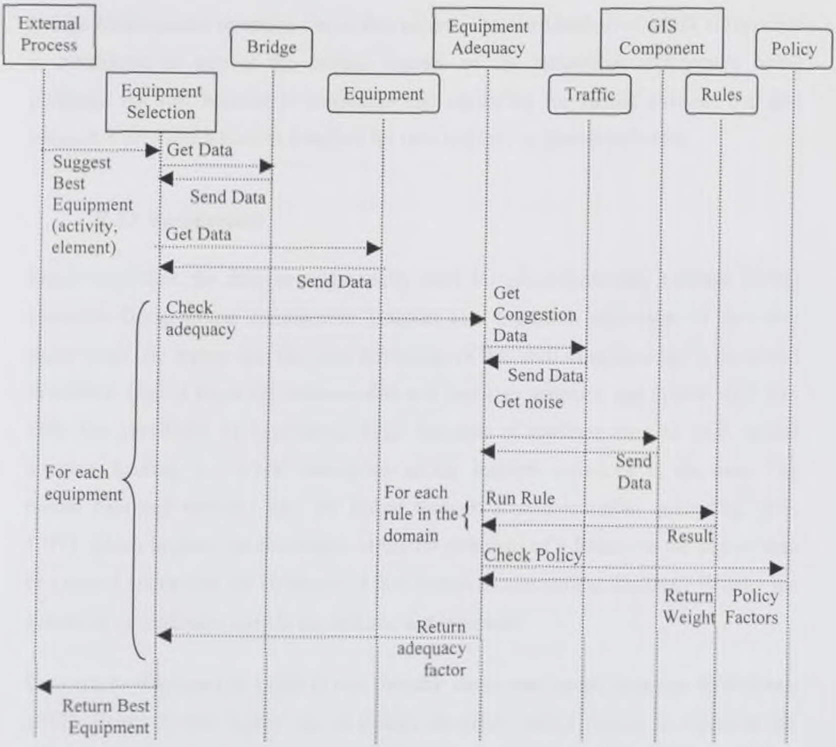

Figure 8.4 – Event trace of Equipment Selection

The author believes that the proposal of introducing object orientation is an important contribution to the development of better systems and this belief will be validated trough the elicitation of expert opinion, as described in chapter 11.

8.3 Geographical Information Systems

As discussed in chapter 7, there is strong support from experts for the introduction of geo-referencing in Bridge Management Systems. She [1997] states that Geographic Information Systems (GIS) have grown enormously in popularity over the past decade, and attributes this popularity to the huge potential of this technology for providing a more adequate environment for analysing and solving problems that are spatial in nature. She [1997] argues that many of the problems concerning the management of

Bridge Maintenance operations have this nature. The introduction of a GIS component is considered as one of the central features of the innovative architecture being proposed not just because it introduces this capability for spatial analysis but also because it provides a natural interface for data display, as discussed below.

8.3.1 Background

Maps have been the devices traditionally used for geo-referencing. Gittings [1998] considers Geographical Information Systems as a high-tech equivalent of the older paper maps. He argues that the main advantage of this shift in technology is the added flexibility. Digital maps are customisable and easier to maintain and update. GIS also offer the possibility of associating large amounts of attribute data to each spatial location, leading to a better description of the features contained in the map. The spatial data and attribute data are linked through a process called geocoding [She, 1997], which implies the correlation of the co-ordinates of a feature in the digital map to a record containing the attributes of that feature in a relational database. Usually the system of co-ordinates used is the latitude and longitude.

Data can be displayed in a GIS in two formats: raster and vector [Bracken & Webster, 1992]. *Raster format* makes use of picture elements (called pixels) to represent the image and is not able to represent individual features but can provide important background information more suitable to the human eye. The *Vector format* on the other hand, maintains or preserves the analogue form of annotation, point, line and area features [She, 1997] and is used to represent individual features. Various GIS systems allow the integration and use of both raster and vector formats simultaneously, but in different layers. Layering is an important aspect of digital maps since it offers an adequate way to organise information and establish a hierarchy for its display.

The possibilities offered by the implementation of a GIS go beyond facilitating the use of maps and the display of data. GIS have evolved from being specialised forms of databases to incorporate analytical spatial models and provide interfaces with powerful query languages to extract meaning from the data stored. As exemplified by Gittings [1998], in a modern GIS one might point at two buildings, ask the computer to describe each from an attached database (that would likely contain much more information than could be displayed on a paper map) and calculate the best route or the distance between them. This constitutes a typical, although simple, example of what is normally called spatial analysis. Bracken and Webster [1992] consider that, by using spatial analysis in an exploratory fashion to provide answers to ill-structured problems, modern GIS tools could be classified as geographical decision making systems. However, a greater use of spatial analysis functions is still required to let GIS become more useful for the development of practical applications [Longley & Clarke, 1995].

Despite this limitation, the U.S. Geological Survey [1997] points out that GIS technology has been used for various purposes, such as scientific investigations, resource management, and development planning. Some researches have advocated the combination of GIS and other reasoning techniques. According to Maguire [1995], this association of the GIS with more conventional technologies can create "new and richer approaches to problem solving". Evans [1993] describes the use of an expert geographic information system combining rule-based reasoning with spatial data representation and analysis. Given all the above, the definition of Jones [1996] of a Geographic Information System as "a combination of computer software and hardware that permits the storage and retrieval, analysis, manipulation and presentation of geographically referenced data" will be adopted in this work.

One of the areas where GIS has been most extensively used is transportation. The amount of research even gave way to the emergence of a specialised group of systems denominated GIS-T, as described by Sutton [1996]. In relation to the specific domain of bridges, the AASHTO [1992] perceives GIS as a tool with considerable potential to enhance management systems. Various researches are trying to translate this concept into practice. Ng and She [1993] discussed the basic concepts and outlined the strategy for the implementation of a GIS-based BMS in Malaysia. Itoh et al [1997] examined the possibility of using a similar approach in Japan.

8.3.2 Description of the Proposed Use in an Advanced System

The proposal of this thesis is to introduce a GIS component that would work in tandem with the more conventional parts of an Advanced Bridge Management System. The GIS component would be connected directly to the Main Interface Object and its most obvious function would be providing a geographical interface for contact with the user. Other methods encapsulated in the GIS component would allow the determination of the spatial effects of maintenance in the surrounding area when necessary. Finally, the map could be used to display some of the results in a way suitable for lay users.

The proposed approach ensures that advanced systems could make use of both beneficial characteristics of a GIS: the geographical interface and the capacity for spatial analysis. The ability of conducting spatial analysis is considered especially important in the context of this work. The use of spatial analytical functions is an important tool to allow a more reliable appraisal of the indirect effects of bridge degradation and obsolescence. It is also fundamental to determine the consequences of the interaction of the bridge with its surroundings during maintenance.

The list of factors that could be more adequately considered by using a geographically oriented interface is extensive. The proximity to certain features such as the city centre or a hospital could increase the importance given to a road and consequently alter the value given to the utility of a bridge in that road, for example. This could be better considered using a spatial function.

Geo-referencing could also help determine if a bridge is located in a certain environment that will cause hindrance to the maintenance operation. In chapter 9 it will be demonstrated that environmental restrictions can have an important bearing in the maintenance cost if special protection or modified work practices are necessary. The advantage of dealing with these features in a map is that can be easily defined and updated and they will only be determined at runtime, avoiding the need to change the values for each bridge in case of alterations in the conditions.

Finally, one of the most important uses envisioned for spatial analysis is the development of routines to calculate the environmental impact of bridge deterioration and maintenance. As seen in chapter 4, the environmental cost is one important factor of the cost-benefit equation that needs to be more properly addressed. Various models are being developed to assess these impacts. All of them are based on certain spatial circumstances and could be better addressed by using a GIS. This would allow the consideration of factors that are not currently taken into account, a fundamental requirement for establishing a consistent value function to evaluate maintenance strategies. Next item shows how advanced systems are expected to make use of this ability.

8.3.3 Example of Use

One of the areas where the spatial capability of the GIS component will be used is the assessment of noise impact. Figure 8.5 illustrates how the assessment of noise sensitivity is expected to work in an advanced system. The bridge location is chosen from the GIS map (it could also be received from the main module). The amount and distribution of noise is defined based on the type of activity and the work method employed using spatial analytical functions. This information is stored in a temporary layer. By combining this area with the data contained in the layer showing the occupation of the area, it is possible to determine the number and type of households in the vicinity of the bridge affected by each level of noise emission. A sensitivity analysis would then help establish the noise impact.

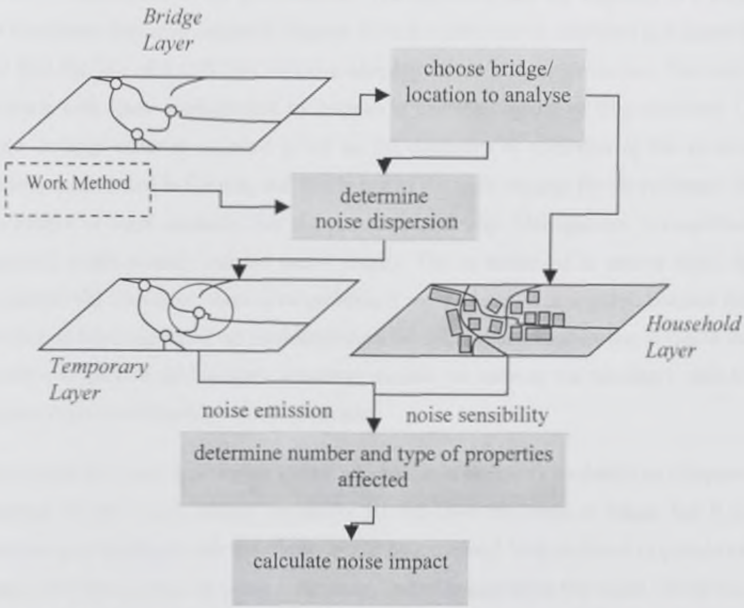

Figure 8.5 – Example of the use of GIS capabilities to determine the impact of MRI operations by means of a spatial analysis of noise dispersion.

The noise impact information could be used to determine the relative adequacy of each work method for that location or could serve as the basis to calculate certain components of the environmental cost of a certain maintenance strategy. The quality of the assessment will clearly be dependent on the amount of data about individual households available. It would be interesting to be able at least to distinguish between industrial and housing units (or areas, if data about individual structures is not available).

Another critical factor would be definition of the method to use to determine the area affected by each noise level. Several sophisticated models for the physical distribution of noise effects have been proposed in the literature. Nielsen and Bloch [1996] discuss the noise buffer technique based on the 'Nordic Noise Model' and propose an improved method that is based on a GIS and uses a building register to calculate the attenuation of noise, adopting a 3-D model. Jones [1996] discusses the use of the CRTN model recommended by the UK Department of Transport (now denominated DTER – Department of the Environment, Transportation and the Regions) in a GIS. He concludes that environmental impacts of road traffic can be modelled and mapped and that the use of a GIS tool can considerably enhance these processes. The main problem with these sophisticated techniques is that the amount of data necessary is large. A large effort is required to set up the databases of attributes of the various features represented in the map and this is one of the main reasons for the resistance in the uptake of these methods. For the purposes of Bridge Management, a simplified approach might already warrant useful results. This is discussed in greater detail in Appendix VII. However, there is no problem if more precision is required because the flexible architecture based on modularization being proposed ensures that it would be possible to include new models whenever desired (as soon as the necessary data to support them is available), without great ado.

Whichever the noise distribution model adopted, it is necessary to define an adequate measure for the noise impact. Appendix III discusses the topic at length but it is interesting to highlight that the impact could be expressed both in terms of people or houses affected as well as using a monetary index to aggregate the result. Given the principles of flexibility and adaptability, it was decided that information in both formats should be stored. It was also concluded that there should be a method for translating them into linguistic variables (such as high, very high and low) to be used in approximate reasoning procedures that would take this factor in consideration, as explained below.

8.4 Approximate Reasoning using Fuzzy Logic and Linguistic Variables

In the opening ceremony of a recent conference in Bridge Management, the director of the British Highways Agency strongly advocated the introduction of more sophisticated and flexible reasoning techniques in Bridge Management Systems [Hayes, 1996]. This work considers that the use of approximate reasoning based on the use of Fuzzy Logic is a useful alternative for attending this demand. Fuzzy Logic has been established as one of the leading research fields in artificial intelligence [Brule, 1986] and has a great potential to model human impressions in natural language, allowing systems to reason in imprecise conditions, as discussed below.

8.4.1 Background

Fuzzy Logic (FL), or as sometimes also called *Possibility Theory (PT),* was formalised by Zadeh [1965]. As explained by Brule [1985], it proposes a new way of dealing with uncertainty (or imprecision) by introducing the concepts of partial set memberships and fuzzy restrictions. Classical sets are based on clear and unambiguous boundaries and are suitable for various applications, but do not reflect the nature of human concepts and thoughts, which tend to be abstract and imprecise [Jang et al, 1997]. The use of *Fuzzy Sets* smoothes out the boundaries between categories. The basic idea is that membership in one fuzzy set does not preclude membership of another and that the *degree of membership* can vary from element to element. Possibility Theory differs from probability theory because there is no uncertainty about to which set a particular element belongs. On the contrary, it is known with certainty that the element belongs to various sets, albeit in different degrees. The degree of membership in a fuzzy set is traditionally established as varying between 0 and 1. A *membership function (MF)* is used to express the relationships of a specific element with the various sets being considered, defining what is normally called as a fuzzy number. The most suitable shape of the membership function will depend on the application, but a linear function is usually convenient in the majority of applications [Hopgood, 1993].

Approximate Reasoning

The concept of fuzzy sets is implemented in reasoning by using fuzzy restrictions, i.e., fuzzy relations that act as an elastic constraints in the values that might be assigned to a linguistic variable. "John is young" can be seen as a fuzzy restriction that establishes "young", a fuzzy subset of the real line, as the value for the implicit attribute "age" of the entity "John". The set of operations involving fuzzy restrictions furnished the conceptual basis for the establishment of a fuzzy logic, which can be seen as the mathematical equivalent of the human approximate reasoning.

Linguistic variables

Fuzzy Logic has been used in many fields, especially in problems associated with the control or automation of systems and reasoning using linguistic variables. In the scope of this work the ability of working with natural language statements is considered the most important. Fuzzy Logic is considered as one of the most suitable ways to address the uncertainties caused by the vagueness in the use of language [Hopgood, 1993]. Cabrera and Kim [1995] argue that FL can manage linguistic concepts in a way that resemble the natural reasoning structure of human beings and, in this way, allow the construction of a more adequate model of reality. The flexibility of this approach is appropriate to model the information contained in statements such the "water is hot" or "sally is tall" [Jang et al., 1997]. Because of this capability, this technique plays an important role in representing human thinking and the communication of information and knowledge in real situations, as forewarned by Zadeh [1965] in its inception. The concept of linguistic variables is used as the basis to codify and analyse commonly used knowledge incorporated in heuristic rules such as "if the water is slightly hot you must reduce the heat a little". An inference system is necessary to use these heuristic rules to extract knowledge about a real problem. Crisp inferences are usually based on the use of predicate logic, using the Modus Ponens inference rule:

IF (X is A) THEN (Y is B)

When X is known to be equal to A it is possible to conclude that Y is B. The problem is that in many real situations X is not exactly equal to A, but to A*. The traditional Modus Ponens inference rule does not permit reasoning in this case. Fuzzy logic can help tackle this problem in two ways, as follows.

Fuzzy reasoning by similarity

The first reasoning strategy, that will denominated similarity method, consists in considering the applicability of the rule as varying between 0 and 1 depending on the similarity between the rule and the situation at hand. In this way, instead of discarding the rule it is possible to qualify the conclusion if A is similar but not equal to A*. This is done by defining A and A* as two fuzzy numbers and comparing them, establishing the *degree of confidence or firing power (FP)* of the rule. The FP is normally given by the maximum membership of the set resulting from the fuzzy intersection of A and A*.

Fuzzy reasoning by extension

The main problem with the "firing strength" approach is that the universe of responses is limited to the interval containing the original conclusions. If a rule states that if noise is high we should reduce the volume a little, this procedure will never recommend that the volume be reduced a lot if the noise is very high. This limitation is overcome if the "compositional" approach is adopted. This consists in using a procedure that produce responses beyond the ones contained in the rules by exploring the relationships between A and A*. This can lead to conclusions such as "if X is A* then Y is equal to B*". For this it is necessary to use more sophisticate inference procedures. Chang et al. [1988] recommended the use of the *compositional rule of inference* suggested by Zadeh [1975]. This implies the use of a fuzzy operation to compose the fuzzy set B* from the fuzzy set A* given the fuzzy relation R_s established between A and B by the original fuzzy production rule. This works out as follows.

$$B^* = A^* \circ R_s \qquad \text{(Eq. 8.1)}$$

Using the compositional rule of inference a fuzzy inference system can use the past known behaviour of a system to determine the behaviour in an unprecedented situation. Some of the most well known fuzzy inference systems that use extension are the ones proposed by Mamdani, Sugeno and Tsukamoto [Jang et al., 1997]. The last two do not follow strictly the compositional rule of inference. They are however frequently used in computer applications because they produce crisp outputs directly, without the need for defuzzification, reducing therefore the computational effort.

8.4.2 Description of the Proposed Use in an Advanced System

While there is not rigorous guidelines about how to develop, implement and evaluate a fuzzy inference system, the empirical results tend to demonstrate the utility of these initiatives [Jang et al., 1997]. Cabrera and Kim [1995] have proposed a fuzzy expert system to assess the condition of concrete bridges that provided useful advice. Arguing that intangible and qualitative features such as the experience and judgement of the inspector need to be consider more adequately, they concluded that the use of Fuzzy Logic was one effective way to improve the assessment process. Bowles and Peláez [1994] discuss the application of FL to systems reliability and demonstrate that probability theory alone is not sufficient to deal with the problem of subjectivity. Arguing that the use of natural language expression offers a more powerful approach to handle the uncertainties, they conclude that reliability information can be more adequately expressed using fuzzy sets.

This thesis proposes the introduction of components capable to manipulate with fuzzy sets and perform fuzzy inferences to provide advanced system with the capability of working with linguistic variables and undertake approximate reasoning. Since approximate reasoning is an invaluable tool to deal with the vagueness intrinsic to subjective opinions and fuzzy rules are a very adequate way to model empirical knowledge this would allow the systems to work with imprecise or incomplete information, enhancing their flexibility. It would also qualify advanced systems to make sensible "guesses" about the probable course of action or the consequences of certain conditions in the cost and performance of bridge maintenance operations.

Construction and Storage of Rules

The first issue to be discussed is how expert will be stored in the form of rules. A flexible rule database will be created that allow the continuously introduction of new rules by the user, as discussed in Appendix V. The initial structure of this databases assumes that each rule could have up to three antecedents. A rule would therefore be represented using the following format:

(rule number, domain, weight, type(arg1), code (arg1), val (arg1), type(arg2), code (arg2), val (arg2), type(arg3), code (arg3), val (arg3), type(res), code (res), val (res))

Each argument is identified by a unique code that indicates the object and property to be considered (for example, code 34 indicates Activity(Cost)). The type indicates if the argument is fuzzy or crisp and is used to direct how that part of the rule is evaluated. The domain is used to ensure that just the rules applying to a certain type of problem are considered, quickening the search for the applicable rules. Some domains have already been established, such as method selection, equipment selection and noise assessment but the user could create new ones. Finally, the weight indicates the confidence on the rule. And will be used to strengthen of weaken the result of the rule in relation to the result of other rules

Construction of Membership Functions

For a fuzzy inference system for Bridge Maintenance decision-support to be established, it would be necessary to define structured ways of expressing certain bridge data in terms of linguistic variables, so fuzzy operations can be undertaken on it. Suppose the existence of the following rule: "if traffic_volume is *high*, than probability_congestion is *high*". The rule would work well if imprecise information about the traffic volume is available. A personal assessment from the user or an examination of the characteristics of the bridge by the computer could result in an estimate about the traffic volume. However, if precise information about the traffic volume is available (for example, that the traffic volume is 2200 cars/hour) the rule is not applicable unless there is a translation mechanism to transform the crisp value in a linguistic statement. To this end it was considered necessary to construct membership functions to each of the parameters involved. The membership functions can then be used to translate the crisp data in linguistic variables for processing by the fuzzy inference engine. Naturally, the user should always be offered the opportunity to override or adjust these functions, according to the principle of interactivity.

Cabrera et al. [1993] demonstrated how membership functions for certain bridge characteristics can be established. They defined MFs for several of the parameters involved in the assessment of bridge conditions using linear functions with a triangular shape based on the recommendations of Kuz'min [1981]. Similar procedures were used to determine the membership functions used in this work. Each MF represents an interval in the possible universe of values of the bridge parameter under discussion that is seen as compatible with the linguistic variables adopted to represent it.

A set of 10 basic linguistic variables was used: Extremely Low, Very Low, Low, Fairly Low, Medium, Fairly High, Very High and Extremely High. It was decided to dissociate the meaning of the linguistic hedges from the concentration and dilation operations, as done by Cabrera et al [1995]. An example of the set of MFs used for defining fuzzy restrictions on the height of a bridge can be seen in figure 8.6. As seen in the figure, trapezoidal linear functions were used to define the fuzzy restrictions. Four points define these functions: origin, beginning of maximum, end of maximum, end. These are the values stored in the database to represent each particular fuzzy restriction.

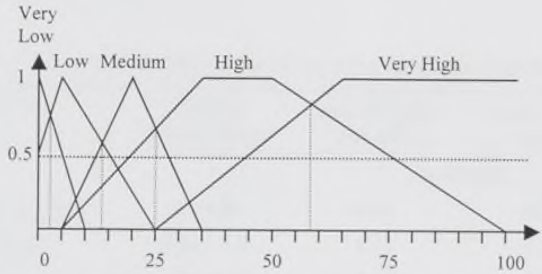

Figure 8.6 – Example of membership function adopted to fuzzify crisp variables.

Standard Membership Functions for Subjective Parameters

Many of the variables that will be involved in the approximate reasoning process are not crisp and objective but fuzzy and subjective in nature. Their membership function could not therefore be constructed in the way described above. A generic scale was utilised to represent such variables. The universe of discourse (or variable domain) chosen was the interval 0-10, which can easily be reduced to the interval 0-1, establishing a relationship with the degree of membership, or expanded to the interval 0-100, which is used in certain condition scales such as the sufficient index.

To construct the generic fuzzy membership function numbers a survey of opinions about how the linguistic values used could be translated in a 0-10 interval was carried out. Fuzzy numbers were constructed based on the results and checked to verify their consistency when submitted to some usual fuzzy operations. The detailed membership functions obtained are given in Appendix VII, but the meaning of the results was summarised in table 8.2. As seen in the table, the intervals where each of the fuzzy restrictions is dominant are sensible and the support values obtained by calculating the centroid of the area defined by the fuzzy restriction in the interval of discourse were contained inside the zone of dominance of the variable they represented, showing consistency. The author considers that these values, while not universal, are more representative of the impression held by people about the meaning of the linguistic variables than a normalised function modified by hedges and they will be adopted in this work. The last column shows that even when the tail constrained memberships are used (where the membership function of the two extreme values in the upper and lower bounds are modified so their congruence with the low/high values is always) they are still basically logical because their centroids fall inside the prevalent range of the qualifier they are associated with.

Table 8.2 – Generic support values for linguistic variables.

Qualifier	Prevalent Numeric Range	Support Value (no tail)	Support Value (tail)
		(centroid)	
Extremely Low	0 – 0.86	0.83	0.83
Very Low	0.86 – 1.5	1.41	1.34
Low	1.5 – 2.90	2.42	2.19
Fairly Low	2.9 – 3.83	3.56	=
Slightly Low	3.83 – 4.66	4.31	=
Medium	4.66 – 5.66	5.17	=
Slightly High	5.66 – 6.78	6.47	=
Fairly High	6.78 – 7.69	7.51	=
High	7.69 – 8.40	8.04	8.31
Very High	8.40 – 9.14	8.59	8.65
Extremely High	9.14 – 10	9.19	9.202

Rule Processing

Having established a way to define linguistic variables for each parameter to be considered, it is still necessary to define how the reasoning will occur. The author investigates several inference mechanisms such as the max-min operation suggested by Zadeh [1975] and the standard sequence suggested by Mizumoto [1982] and used by Chang et al [1988]. The majority of the relations examined were not fully satisfactory. Due to this fact the author decided to adopt a conservative view and use the simple reasoning by similarity. To overcome the boundary problem associated with this type of analysis it is recommended that rules should be created for various different input conditions (normally high, low and medium). If possible, rules should be constructed to the extreme situations. In this way, the performance of the inference mechanism is improved. Even with a small set of rules, the performance of the fuzzy reasoning procedure proposed is already good, as will be demonstrated in chapter 11.

A rule will frequently have multiple antecedents. This fact will be addressed by processing each of the antecedents as an independent rule and combining the results using a fuzzy addition operation, as suggested by Kosko [1994]. The firing power will be used to adjust each result before aggregation, as proposed by Jang et al [1997]. This approach is justified by the intuitive notion exposed by Graham and Jones [1988] that the consequent clause should never be true to a greater degree than the antecedent clauses. The standard membership functions discussed above will be use to interpret the consequence of the rule but it is envisioned that alternative memberships functions could be introduced by the user.

One advantage of this fuzzy inference mechanism is that when the parameters of the rule are not defined in a crisp way anymore, it is possible to fire several previously mutually exclusive rules simultaneously. This can provide a more consistent result by avoiding the sharp transitions between the resulting actions caused by the use of crisp rules. When combining the results of the various rules, the weight given to each of the competing rules is determined by the degree of confidence. It is necessary to make the *aggregation* of the various consequences, as follows.

Aggregation of the Results of Different Rules

The reasoning mechanism proposed will be based on the consideration of a series of production rules concerning each topic. The rules will be extracted from a database containing a large series of rules organised according to their domain of relevance, such as equipment selection, congestion forecast, etc. Each of the rules of a particular domain will be processed in turn. In the end, various assessments about the particular domain would be obtained. The crisp ones would generate a binary result on the extreme of the interval of discourse (1/0 or 10/0 depending on the scale used) while the fuzzy rules could result in intermediary values of confidence.

The result of the analysis of the set of rules regarding congestion could for example be a vector indicating that the probability of congestion given the current circumstances is [high, low, high]. The aggregation of these results will be made be multiplying the support values of each result (8.04*2.42*8.04). The product operation was chosen because if one of the partial adequacies were zero (indicating that the equipment is not adequate at all according to that factor), the total suitability would be null. The total result is obtained by extracting the n-root, where n is the number of partial results being considered, in this case three. This would result in an equation of the form:

$$TFR\ (D_x) = \{\Pi\ [PFR(R_y)^{(RIy*FSy)}]\}^{(1/\Sigma(RIy*FPy)}\qquad \text{(Eq. 8.2)}$$

Where: TFR is the total fuzzy result for domain Dx; RIy is the importance of Rule Ry, PFR(Ry) is the partial fuzzy result for rule Ry of the domain Dx; and FSy is the firing strength of rule Ry

Table 8.3 demonstrates the robustness of the arithmetic proposed. It considers three rules that have as a result respectively "medium", "high" and "very low". The support values for these rules would be taken as 0.517, 0.804 and 0.141 respectively (extracted from table 8.2 and reduced to the universe of discourse 0-1). It will be assumed that the firing strengths of the rules are all 1 (fully applicable). If the rules were given the same importance the final result would be obtained by multiplying the three results and extracting the cubic root. The results in the table show that, if the importance given to each of the rules (expressed by the coefficients w_1, w_2, w_3) varies, the result also varies in a sensible way. For example, if the importance given to two of the rules is none (situation 4), the result will be equal to the value of the remaining rule, as expected. The importance coefficients are interpreted numerically using the 1 as the support value for normal (or medium), 2 for high and 0.5 for low. The other values are obtained using hedges, such as very high = $(\text{high})^2 = 4$.

Table 8.3 – Examples of the use of the product of adequacies

Situation	Importance					Result
	w_1	w_2	w_3		Σw	
1	Normal (1)	Normal (1)	Normal (1)	$(0.517)^{1*1}$ $(0.804)^{1*1}$ $(0.141)^{1*1}$	3	0.388
2	High (2)	Normal (1)	Normal (1)	$(0.517)^{2*1}$ $(0.804)^{1*1}$ $(0.141)^{1*1}$	4	0.417
3	High (2)	Normal (1)	Low (0.5)	$(0.517)^{2*1}$ $(0.804)^{1*1}$ $(0.141)^{0.5*1}$	3.5	0.487
4	High (2)	Normal (1)	None (0)	$(0.517)^{2*1}$ $(0.804)^{1*1}$ $(0.141)^{0*1}$	3	0.599
4	High (1)	Normal (1)	None (0)	$(0.517)^{1*1}$ $(0.804)^{1*1}$ $(0.141)^{0*1}$	2	0.645
5	Normal (1)	None (0)	None (0)	$(0.517)^{1*1}$ $(0.804)^{0*1}$ $(0.141)^{0*1}$	1	0.517

Interpretation of Rules

The results of fuzzy inferences are usually fuzzy numbers. They can be checked against the standard language identifiers to see what linguistic conclusion would be obtained. Sometimes however it might be adequate to express them numerically. *Defuzzification* embodies the transformation of the fuzzy result in a crisp one.

Different defuzzification techniques have been suggested in the literature. One of the most common is the Weighted Mean of Maximums, which consists in averaging the points of maximal possibility of each fuzzy conclusion, weighted by their respective degrees of truth [Bowles & Peláez, 1994]. The most common technique however consists in calculating the centroid of the area obtained by adding the various conclusions [Jang et al., 1997]. Because this produces consistent results [Kosko, 1994] it was chosen to be adopted in this thesis. The linguistic interpretation of an isolated result could be made by checking the intervals of prevalence presented in table 8.2.

8.4.3 Example of Use

One of the opportunities advocated for the use of approximate reasoning in advanced systems is the verification of the appropriateness of various access schemes to perform a certain MRI action. A reasoning model was developed to tackle the problem based on the encapsulation of common-sense knowledge on rules. By examining the way experts reason it was concluded that the adequacy of a certain equipment could be considered as being determined by four basic factors: the technical adequacy of the access equipment for the job, its impact on the users and the environment and the cost (or impact on the agency). The complete model is presented in Appendix VII but figure 8.7 summarises the main characteristics that must be analysed to determine each of these impacts.

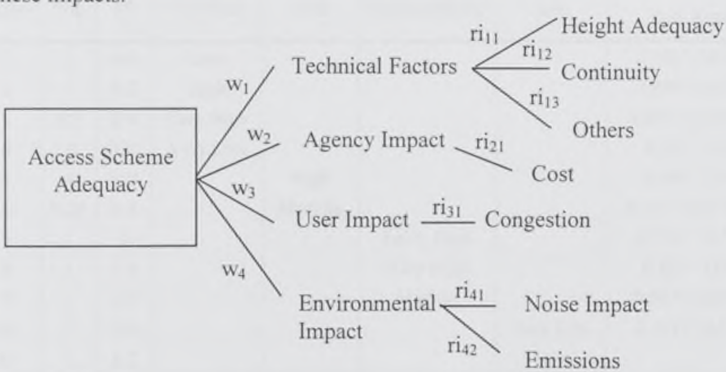

Figure 8.7 – Representation of the factors that affect the choice of access scheme.

To determine the technical adequacy, for example, characteristics such as the height compatibility and continuity compatibility between the equipment and the MRI activity would have to be considered. The knowledge about which combination of characteristics is good or bad is encapsulated in rules such as the ones presented in Appendix VI. To represent the system of values of the user, as discussed in chapter 4, relative weights can be given to the result of the evaluation of each of these factors, as pointed out in the figure.

After a fuzzy assessment of each of these impacts is undertaken, the suitability of the access scheme is calculated by using the fuzzy aggregation operation discussed before. Table 8.4 shows an example of how a model like this would be work. Eleven hypothetical fuzzy production rules would be used to make partial assessments about the value of each factor depending on the characteristics of the bridge. These would then be aggregated to extract the meaning of each domain. As can be seen in the table, the results of the aggregation procedure are sensible. The greater importance given to rules 4 and 5 distort the results in the respective domains in the direction of their results. The greater weight given to the technical domain also influences the final result. Considering the results of the table the suitability of equipment Eq1 to perform the activity A_y in a certain bridge B_x would be fairly low.

Table 8.4 – Example of fuzzy aggregation procedure applied to equipment selection.

			Domain				
Rule	Imp	FS	Technical	Cost	Environmental	User	Rule Result
1	1	0.9	Low				0.242 ^ (0.9*1)
2	1	0.2	High				0.804 ^ (0.2*1)
3	0.5	0.8	Very High				0.859 ^ (0.8*0.5)
4	2	1.0	Very Low				0.141 ^ (1*2)
5	4	1.0		High			0.804 ^ (1*4)
6	0.25	0.2		Medium			0.517 ^ (0.2*0.25)
7	1	0			Fairly High		0.751 ^ (0 * 1)
8	1	1.0			Very High		0.859 ^ (1*1)
9	1	0.8			Medium		0.517 ^ (0.8*1)
10	1	0.6				Very Low	0.141 ^ (0.6*1)
11	1	0.7				Low	
Domain Result			0.22	0.8	0.685	0.189	
Interpretation			Low	High	Fairly High	Low	
Relative Weight given to the domain			High (0.804)	Medium (0.517)	Fairly Low (3.56)	Medium (0.517)	
Final Result			0.346 (Fairly Low)				

By repeating this procedure for each type of equipment available, a list with the appropriateness of each of them for the particular combination of conditions being considered could be defined. In order to simplify the calculations, just a very limited number of rules were considered in this example. The initial set of rules suggested for guiding the selection of access schemes, as well as the ones for each of the other reasoning domains being proposed in this thesis, are given in Appendix VI. There are however just a basic list since, as will be discussed in chapter 10, the architecture being proposed will allow users to implement more rules if they want to.

The model for access scheme selection described above is an example of the type of fuzzy operations that the author believes should be implemented in an advanced system to raise its intelligence. While the procedure is not precise nor the rules exhaustive, the result obtained is adequate to enable the computer to produce a fair estimate of the possible course of action that would be adopted by an expert in a similar situation. This ability can be vital in certain circumstances. For example, the choice of access scheme will normally influence significantly the cost of the MRI intervention under consideration and therefore affect the resulting benefit-cost ratio. The use of approximate reasoning using fuzzy logic and linguistic variables to produce an answer is considered necessary because some of the factors are subjective in nature while precise data about others might not be available. The author argues that the answers provided in this way, while not precise, will be sufficient to improve the quality of the decision-making by extending the scope of factors considered. This assumption will be tested in Chapter 11 - Validation.

8.5 Summary

An innovative architecture for Advanced Systems was outlined in this chapter. A modular structure based on the use of object orientation was analysed and the concepts of data and procedural objects introduced. The new capabilities offered by the introduction of a GIS component were examined and an example used to demonstrate how this tool could be used to undertake spatial-based analysis and provide invaluable information about the environmental impacts of MRI operations. The author also demonstrated how fuzzy reasoning could become a fundamental way to incorporate the unstructured knowledge used by human experts in real decision-making. An application for the selection of access schemes and work strategies was then discussed.

Proposal of an Improved Model for Economic Appraisal of MRI options in Advanced Systems

9.1. Introduction

A framework for change was established in chapter 7 to guide the production of Advanced Bridge Management Systems. It emphasised the need for the development of improved Economic Appraisal procedures in line with changing society perceptions and compliant with the emergence of *Value For Money* policies discussed in chapter 4. This chapter presents a proposal for an improved Cost-Benefit model for Economic Appraisal. The model is based on a broad view of the effects of bridge deterioration and maintenance. It also considers the financial impact of the expenditure and suggests the introduction of a factor to consider the external cost of interventions. The author suggests, to support the model, the adoption of a utility function to express the effects of changes in the condition of the bridge and the establishment of a new classification for agency expenditure.

9.2. Development of the New Model for Economic Appraisal

The first step in the process of formulating the new model was to define the adequate format for it. Existing Bridge Management Systems frequently adopt cost minimisation models with a linear format for supporting maintenance strategy decision-making. The author recognises that the most appropriate format for an appraisal model is ultimately dependent on the objectives established by users for the Bridge Management process, as emphasised in chapter 4, and that cost-minimisation or other linear methods can be useful in certain cases. Nonetheless, as discussed in chapter 5, authors like Mackie [1998a] express reservations about the use of linear models when it is necessary to make a prioritisation of competing alternatives in the presence of a limited budget. In these cases, it is recommended the use of an incremental benefit-cost ratio such as:

$$\text{IBC} = \Delta\text{Benefit} / \Delta\text{Cost} \qquad \text{(Eq. 9.1)}$$

Since the effects of MRI alternatives can be either positive or negative, it was considered adequate to interpret the equation above as being expressed in terms of net costs and benefits, as follows:

$$\text{IBC} = (\Delta\text{Benefits} - \Delta\text{Disbenefits}) / (\Delta\text{Costs} - \Delta\text{Savings}) \qquad \text{(Eq. 9.2)}$$

One important advantage of using the ratio format is that it is fully compatible with the notion of Value for Money. If all the social benefits and disbenefits were considered, the first part of the equation could be interpreted as expressing the increase in value brought by a MRI certain course of action that originates the cost and savings registered in the second part. Since savings can be seen as a type of benefit, they could be brought to the topside of the equation, avoiding the possibility of a negative value index being registered if they surpass the costs. Equation 9.2 was therefore rewritten to express the value index VI of a MRI intervention alternative MAI_x as:

$$\text{VI}(\text{MAI}_x) = (\Delta\text{Benefits} + \Delta\text{Savings} - \Delta\text{Disbenefits}) / \Delta\text{Cost} \qquad \text{(Eq. 9.3)}$$

This will be the generic format for the model to be developed in this chapter. Costs and savings are the financial consequences of adopting a certain MRI action and are naturally expressed in monetary terms. The benefits and disbenefits meanwhile are the representation of the non-monetary effects of the action. In order to allow a direct comparison with the costs and savings the benefits and disbenefits should be expressed, whenever possible, in monetary terms. If this is not feasible then an analysis on economic terms becomes impossible and it is necessary to revert to a more subjective analysis using an alternative approach such as the framework analysis, discussed in chapter 4. Given the importance of having objective measures to guide the process of MRI strategy formulation, as emphasised in chapter 5, this thesis will strive to show that it is possible to use the proposed model in an economic basis.

9.2.1 Elements of the Model

Having established the format of the model, the next step is to define the scope of the effects to be considered. While there might be several possible alternatives for tackling a certain bridge problem, ranging from small interventions to total replacements, in relation to the definition of costs and benefits all of them can be seen in a similar way, as discussed below.

At the decision moment T_0 the bridge is in a certain Condition State CS_0. As discussed before, each Condition State should be associated with a certain level of performance and therefore to a certain degree of risk. The relationship between these factors is given by a utility function, as discussed in chapter 5. Appendix II discusses how to define and use a utility function for bridges. At this point it is sufficient to understand that when the bridge condition deteriorates the utility is also expected to decrease and vice versa. Therefore, if no action is taken at T_0 and the deterioration increases with the passage of time the utility will be progressively reduced. On the other hand, if a MRI action is carried out and causes an improvement in the Condition State, it will increase utility. This fact will be expressed by a factor denominated *variation in bridge utility (VBU)*.

When the deterioration reaches unacceptable levels, the service life of the structure is considered as finished and, if no repair action is undertaken, it is necessary to replace it. This generates a monetary expenditure that is designated in the figure as the cost of replacement (CR). The replacement of the bridge causes an interruption on the transportation function and the monetary expression of this negative impact on the users, the society and the environment will be designated as the external cost of replacement (ECR), according to the definition of external cost given in chapter 5. By improving the Condition State of the bridge, MRI interventions normally extend the life expectancy and therefore dislocate the need for replacement to the future. Because of the value time of money, this could be expressed as a cost reduction or a saving. This impact will be encapsulated in a factor denominated *variation in replacement cost (VRC)*. The external cost of replacement will be equally dislocated but because it is a non-monetary quantity, it does not have a time value and therefore will not vary. For this reason it will be not considered in the Value Index equation.

Nonetheless, the intervention itself will also have a negative impact on the performance function and a factor called *External Cost of the MRI intervention (ECI)* was introduced in the model to represent this fact. MRI interventions will need to be financed and the *Monetary Cost of Intervention (MCI)* is the factor used to represent the whole of the agency expenditure with the MRI intervention. Hypothetically, this expenditure could be distributed over time but for the moment it will be considered as a concentrated lump sum incurred at the beginning of the planning horizon.

Finally, there are the financial consequences of investing money in the intervention, which will be represented by the opportunity cost. Opportunity cost is defined by White et al. [1998] as the cost of forgoing the opportunity to earn interest, or a return, on the resources invested. The *Opportunity Cost of Intervention (OCI)* will be a factor that represents in the model the fact that a certain monetary return would have been earned if a similar amount to that used to finance the MRI intervention was invested at some pre-determined interest rate during the period covered by the analysis. The user should ordinarily make the definition of the relevant rate of interest but, in the absence of this information, the standard value adopted will be the basic rate of interest published by the government, as discussed in 9.3.3. If the interest rate adopted includes inflation, the net rate of interest should be calculated. According to Dale [1993] this can be done as follows:

$$nr_i = [\,(1+r_i)/(1+i)] - 1 \qquad \text{(Eq. 9.4)}$$

Where nr_i is the net rate of interest, r_i is the rate of interest and i is the rate of inflation.

Using the definition of impacts discussed above, the generalised form of the model for the variation in value (or economic efficiency) of a MRI intervention alternative MAI_x would be:

$$V(MAI_x) = (VBU + VRC - OCI - ECI) / MCI \qquad \text{(Eq. 9.5)}$$

Where: VBU is the monetary expression of the variation in bridge utility. ECI is the monetary expression of the external cost of the MRI intervention. OCI is the opportunity cost of the investment in the period; MCI is the expenditure incurred by the agency during the MRI intervention. VRC is the variation in the discounted replacement cost.

It is postulated that this formulation should be valid to all investment alternatives. Since doing nothing must always be considered as an option during the definition of maintenance strategies, as suggested by Obaide and Smith [1994] and Merna and Owen [1998], it is necessary to check the validity of the model for this option. It was immediately verified that some factors should have a slight different interpretation if the do-nothing option is considered. Care must be taken for example with the fact that the variation in the replacement cost should be considered positive if there is an extension of service life and negative if there is a reduction, changing from representing a saving to represent an additional cost. It was therefore considered necessary to customise the model as follows.

9.2.2 Customization of the Model for the do-nothing option

Since, in the absence of maintenance, the condition of the element will tend to degrade, with effects on the utility and the lifetime of the structure, this thesis considered that the do-nothing alternative should not be considered just as a passive option. The decrease in utility during the analysis interval because of inaction will compose the disbenefits of doing-nothing. In some CBA formulations it is assumed that the foregone benefits because of the lack of maintenance should constitute the cost. This thesis will not adopt this stance, preferring to maintain the variation in utility in the upper side of the model because it is a non-monetary expression of value (or loss of value). Instead, the cost of doing nothing will be defined as the financial increase in replacement cost generated by the decrease in lifetime expectancy that generally occur in the absence of a MRI intervention. There will obviously be no external cost of doing–nothing.

The benefits of doing nothing should instinctively be few. In fact, some models do not assume the existence of any benefit at all. However, if the do-nothing option is chosen and the money equivalent to the expenditure that would be incurred in the undertaking of the MRI alternative with the best IBC ratio is not allocated, it could theoretically be invested and used to generate a return. The opportunity cost in this case would be negative, which could be interpreted as indicating an opportunity gain. Nonetheless, since a public authority would most probably not effectively invest the money in the market but use it in an alternative way, this return is just potential and not real and will therefore be maintained in the top side of the value equation. Table 9.1 summarises the classification of the effects for each of the two basic types of action.

Table 9.1 – Classification of effects for each of the basic courses of action.

	Benefits	Disbenefits	Costs	Savings
Do Nothing	OCI	(VBU)	VRC	0
Do Something	(VBU)	ECI + OCI	MCI	VRC

9.3 Detailing of the Appraisal Model

This section clarifies some of the details regarding how the economic appraisal model proposed above will be used in practice.

9.3.1 Planning Horizon

As pointed out by White et al. [1998], to conduct a proper appraisal it is necessary to consider the various investment alternatives over a same period of time, defining what is commonly denominated as the planning horizon of the analysis. The choice of planning horizon is ultimately a decision of the decision-maker but the stance taken in this thesis is to suggest the use of relatively short planning horizons. This recommendation is based on the fact that changes in technology, in the characteristics of the structure and in the relative value attributed to the various benefit elements will probably occur during the planning horizon. These changes are generally very difficult to forecast and, as indicated by White et al [1998], this fact tends to make the analysis of long-term effects a dubious exercise that can lead to misleading results.

The adoption of a short planning interval is also justified by the fact that the established objective of the appraisal analysis is not to determine the most economic alternative for each bridge in the long-term but to define the best allocation of money to maximise the utility of the stock in the short term. The author believes that this objective is more adequate because it is synchronised with the desires of public authorities and the public, which tend to show themselves more willing to receive benefits in the short term.

Consequently, in the absence of a user defined choice, the standard planning horizon chosen for the model will be 5 years. The choice of this value was based on the analysis of the recommendations of the road user charter in the UK [Highways Agency, 1994], which states that authorities should try to avoid making more than one intervention in the same bridge during this interval. If this recommendation is followed, the minimum interval between the decision points for intervention in a bridge would be 5 years and that would imply that, having made a decision for a certain course of action at time To, it would be necessary to wait for five years to make further interventions to correct or alter this course of action. This means that the balance of cost and benefits in this five years should justify the action being taken now.

9.3.2 Budgeting Horizon

As stated above, the basic objective of an appraisal model is to define the best allocation of the budget among a portfolio of bridges. The most important information produced is how to distribute the money available at the present moment to maximise the increment in value. However, information about future works might also be important for strategic purposes and to allow authorities to prepare the sites for the intervention as required by law. It is therefore argued that advanced systems should provide not just information to support the allocation of resources in the present budget exercise but also for a certain number of budget exercises in the future. This time interval will be denominated as the budgeting horizon. The adequate budgeting horizon will depend on the needs of the user. Nevertheless, considering that PONTIS uses a ten-year interval and that this is compatible with the fact that budget is made available at one or two-year intervals, this thesis assumes an standard value of 10 years for the budget horizon. This interval is considered suitable to provide users with an idea of the probable future set of bridges to be rehabilitated. Considering that the standard planning horizon is 5 years, as discussed in 9.3.1, at the end of the budgeting horizon it would be necessary to make predictions about the variation in bridge utility 15 years in the future.

9.3.3 Discounting

As pointed out by Robinson [1993], taking maintenance decisions in a rational basis requires the comparison of different alternatives for investment at the present time with their respective consequential future effects. As stated in chapter 5, money has a time value [White et al, 1998] and therefore the temporal distribution of costs needs to be considered. Dale [1993] argues that the use of a discounting factor is a suitable method to homogenise costs in relation to the time of their occurrence. Using a discount rate all monetary elements of the appraisal model can be brought to the same point in time.

This thesis advocates that the various effects related to MRI alternatives should be brought to the beginning of the planning interval, as represented in figure 9.1. This procedure was chosen because users would normally have a more accurate idea of the present value of money.

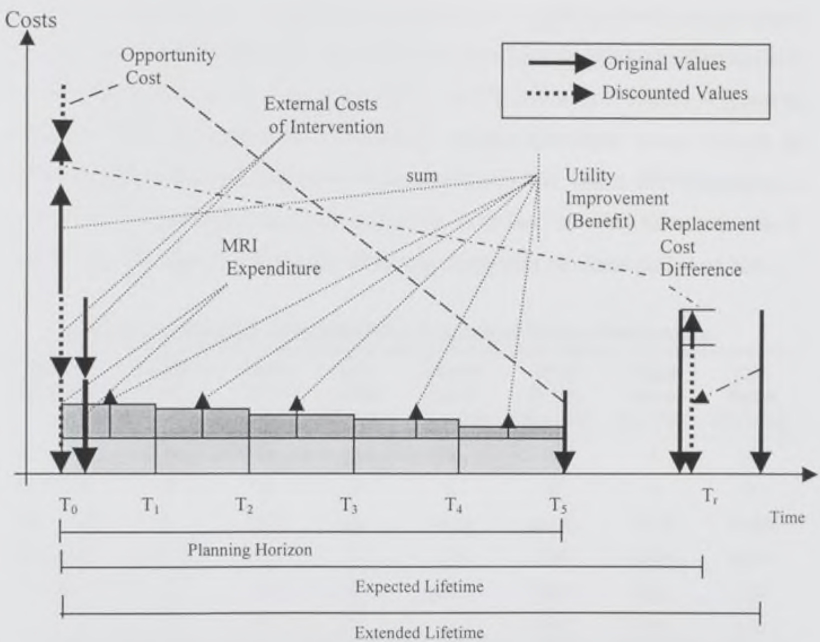

Figure 9.1 – Discounted Profile of the Elements of the Appraisal Model

As seen in the figure, the variations in utility will not have to be discounted, since they are being transformed in monetary values using current values. By the same principle, the variation in external costs also dispenses discounting. If the maintenance expenditure is assumed as concentrated and is incurred near the beginning of the interval, there is also no need to discount it. But if it is distributed over time or occurs at a later date then it is recommended that they should be aggregated year by year and discounted. The opportunity cost should be calculated at the end of the interval and then discounted to the beginning, as pointed out in the figure. Finally, the variation on the replacement cost is calculated by comparing the discounted values at t_r (the expected lifetime before the intervention) and then discounting the difference to the beginning of the planning horizon. The discount rate to utilise must be defined by the user. As discussed in chapter 5, this might be a controversial choice, since there are serious doubts about the proper rate to utilise.

9.3.4 Probabilistic Effects

Following the concept of a probabilistic distribution of condition states, as introduced by systems such as PONTIS, the forecast of the Condition State of a certain element with a certain problem in coming years will in fact be given by a matrix of probable conditions. Table 9.2 shows how this matrix evolves over time. Given the set of transition probabilities indicated in the table, an element that, with a 100% certainty, is in state 2 in T_0 would have approximately 13% of chance of being in state 3 after 5 transition intervals and a 0.1% chance of having failed after the same period of time.

Table 9.2 – Example of Probabilistic Forecast of Bridge Performance.

Transition Probabilities	Condition state	Initial (T_0)	First Period ($T_0+\Delta t$)	Second Period ($T_0+2\Delta t$)	Third Period ($T_0+3\Delta t$)	Fourth Period ($T_0+4\Delta t$)	Fifth Period ($T_0+5\Delta t$)
P12 = 1%	1	0	0	0	0	0	0
P23 = 2%	2	0	0	0	0	0	0
P34 = 3%	3	100	97	94.10	91.28	88.54	85.88
P45 = 5%	4	0	3	5.75	8.28	10.61	12.74
Pf = 8%	5	0	0	0.15	0.43	0.81	1.28
	F	0	0	0	0.01	0.04	0.10

This means that the determination of utility will also assume a probabilistic character, with the performance and the probability of failure varying with the Condition State.

9.3.5 The Use of Weights

This thesis defends the utilisation of weights to give users the possibility of customising the model according with their own desires and purposes, as discussed in chapter 5. The modified weighted model would therefore be composed by:

$$VI(MA_x) = (\lambda_1 \, VBU + \lambda_2 \, ECI + \lambda_3 \, OCI + \lambda_4 \, VRC) / MCI \qquad \text{(Eq. 9.6)}$$

The weights indicate the relative importance given by the user to each of the effects represented by each component of the model. To express aversion to a certain kind of effect it is possible to set $\lambda_i > 1$. To represent willingness in obtain such results a $\lambda_i < 1$ can be assumed. If the factor is considered as irrelevant λ_i should be set to 0. The costs are considered as a reference because they are naturally measured in monetary units and therefore do not have any weight.

9.4 Application of the Model

The appraisal model proposed will be used to determine the most appropriate MRI strategy. This thesis defends the idea that the analysis of MRI alternatives needs to be initially made at the project level. The value index for each alternative should be calculated and this data used to determine the best alternative for an isolated bridge. It would then be possible to find the combination of activities that could maximise the "value" obtained for the available budget over the whole network. Having in mind this idea, the procedure indicated in figure 9.2 is suggested for defining the best strategy for the current budget exercise.

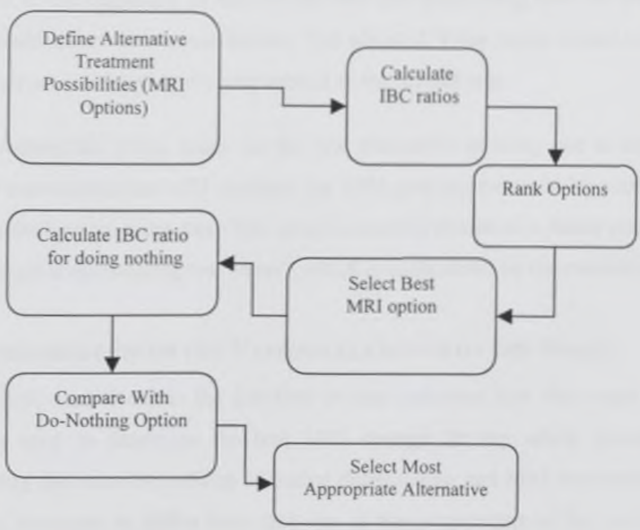

Figure 9.2 – Flowchart of Economic Appraisal

The first step indicated in the figure consists in the determination of the Value Index for each possible MRI intervention strategy suggested by the system or defined by the user for a particular element of a certain bridge. A different value will be obtained for each option being considered since they will have a different balance of costs and benefits. After using these values to select the preferred intervention option, it is necessary to check this option against the do-nothing option.

The two-step procedure is needed because the model for the determination of the benefits of doing nothing demands knowledge of the cost of the "best alternative" option. Having confirmed the preferred course of action for each element, aggregation procedures could then be used to define bigger (and more "valuable") projects, as will be discussed in detail in chapter 10. Having established a set of competing projects, the next step consists in analysing the needs of the entire network simultaneously. It is then possible to determine the portfolio of projects that would constitute the "best value" programme of MRI interventions for the current budget exercise.

In the case of a 2-year budget exercise, some projects will have to be deferred for the second year. In this case, a secondary Value Index must be calculated by discounting all values to the beginning of the second-year and considering how the delay in the action would affect the various factors. The adjusted Value Index would indicate the appropriateness of delaying the intervention to the second year.

Having defined the Value Index for the best alternative in every one of the possible years of intervention the MRI strategy, the MRI programme could be established by using a prioritisation procedure. This would normally consist of a linear programming model aimed at maximising the "value", which is constrained by the available budget.

9.5 Determination of the Various Elements of the Model

The analysis carried out in the previous section indicated how the model proposed could be used to determine the best MRI strategy for the whole network while considering the numerous effects of bridge deterioration and MRI interventions. It is, however, necessary to define how each one of the components of the model will be determined. It is important to highlight again that, for a consistent economic analysis to be made using the appraisal model proposed, it is necessary to define how the monetary expressions of the various impacts will be calculated, as pointed out by Snell [1997]. The costs and savings are already in a monetary unit and might just need to be discounted to extract their time value. The monetary value of the benefits and disbenefits however needs to be determined using some kind of valuation procedure. The following item discusses how a monetary value would be attributed to each of the elements of the proposed model.

9.5.1 Variation in Bridge Utility (VBU)

The Bridge Utility is estimated using a Bridge Utility Function, as discussed in chapter 4. The function encapsulates the system of values expressed by the user and uses it to express in monetary terms the importance attributed to a bridge. This importance will vary according to the level of performance offered by the bridge, which is in turn associated with the Condition State of the structure. However, it is not the utility of the bridge but the variation in utility that it is necessary to determine. The positive impact of a MRI intervention revolves around the avoidance or reduction of the undesirable effects of deterioration. This means that when maintenance is undertaken the factors that reduce utility are minimised and the utility of the bridge is increased. Figure 9.3 shows that if at T_o a MRI action is taken the condition will improve and there will be an increase in utility.

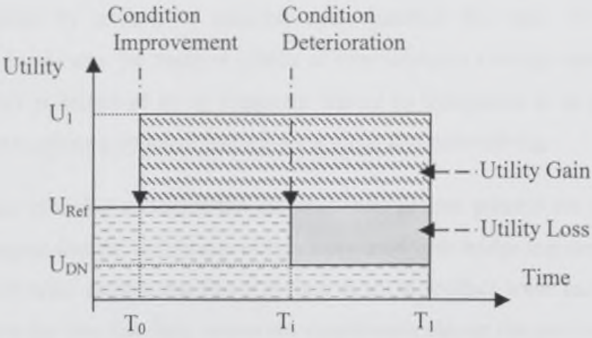

Figure 9.3 – Relationships between bridge condition and utility.

If no action is taken then there is a risk that at some point T_i during the planning interval the condition will deteriorate further and there will occur a utility loss. Theoretically, if the condition did not change during the interval of the analysis, the utility would be constant and the variation in utility would be zero. However, this is not possible because a probabilistic structure is used to forecast the future condition states, as discussed in item 9.3.4. The figure also illustrates the fact that, because discrete intervals are used for the condition states, as discussed in chapter 2, the reduction in utility will not be continuous but it will occur in steps. Section 9.6 discusses at greater length how to calculate the variation in utility.

9.5.2 External Cost of Intervention (ECI)

The external cost of intervention is a factor that was not considered formally in any appraisal model examined by the author during the execution of this thesis. This factor nonetheless seems to influence the behaviour of bridge authorities, as verified in the discussion with the experts. Various of the experts interviewed relied upon engineering judgement to determine the need for intervention and their perception about the appropriateness of acting or not is clearly influenced by the amount of disturbance caused by the action. This was proved by a reasoning exercise that asked experts to chose between intervening or waiting to act in a bridge. Just when the damage was extensive the majority of them choose to intervene in a very busy structure. In this case they indicated that they would prefer to do all the work necessary in the bridge in one go, even if some elements were not yet considered to be at the point were their rehabilitation would bring the best economic return. The demonstration of the importance given by experts to external costs justifies the idea of pursuing improvements in the way the negative effects of intervening in a bridge structure are considered. This is perceived as an important feature to implement in an advanced system in order to create a structure that supports social decision-making.

The importance of trying to model the external costs is also pointed out by Jones [1996], who argues that the deleterious effects associated with bridge maintenance are accepted as very wide ranging but that it is time to try to produce some hard data to support or refute the idea that these values can significantly change the prioritisation of works. The determination of the value of the external costs is not an easy task. However, it is not necessary to increase the precision of the cost assessment significantly, since the strategic character of Bridge Management policy establishment does not warrants it, but the emphasis instead should be to try to include all factors possible. This thesis considers that, utilising the concept of Bridge Utility and making use of the capabilities introduced by the innovative system architecture proposed in chapter 8, it is possible to develop procedures that, while approximate, would be capable of providing an adequate estimate of the ECI. The main components of the ECI are the user costs and the environmental costs, since society costs will are not going to be considered directly, as explained in chapter 4. The ECI will therefore be modelled as:

$$ECI = \Delta\,(\text{User Cost}) + EI \qquad \text{(Eq. 9.7)}$$

The increase in user costs can be seen as originating from two main effects: congestion and detour. The main negative effects of congestion in users are delays, increases in the operational cost and in the risk of accidents. Detour causes extra expenditure and increases in travel time because of the longer route. The increased risk of accidents because of the increase time in the road must also be considered.

The environmental cost meanwhile is composed fundamentally by the monetary expression of the increase in noise levels and the higher amount of atmospheric emissions. Chapter 10 discusses how these two factors will be calculated in the advanced system denominated ORIGAMI that is going to be outlined in the later parts of this thesis. Other environmental impacts might exist but they are normally more be difficult to assess, especially when they are diffuse or subjective, such as the loss of habitats or the occurrence of visual pollution. In these cases, it might be necessary to assume a lump sum given by the user to represent them until better models are developed. If this is not feasible, it might be necessary to disregard them altogether.

9.5.3 Opportunity Cost of Investment (OCI)

If MCI is the maintenance expenditure, T_p is the planning horizon, r_c is the interest rate on the capital invested and r_d is the discount rate, the opportunity cost of investment could be defined as:

$$OCI = [((1+r_c)^{Tp} - 1) / (1 + r_d)^{Tp}]\ MCI \qquad \text{(Eq. 9.8)}$$

The basic question is which interest rate should be adopted to represent the fact that resources are being used in bridge maintenance and will therefore not be available for alternative uses in other public areas (or vice versa in the case of an opportunity gain).

This thesis will assume that the basic rate of interest prevailing in the market should be assumed, but the user could customise this value if desired.

9.5.4 Monetary Cost of Intervention (MCI)

The procedures utilised for cost assessment in existing BMSs are often simplistic, as discussed in chapter 5. A revised way of assessing the agency expenditure is seen as one of the priorities in developing more advanced Bridge Management Systems. Having a reliable way of calculating agency costs is considered fundamental for providing a realistic assessment of the amount of work possible with the available budget. This will be discussed in greater detail in section 9.7.

9.5.5 Variation in Replacement Cost (VRC)

The determination of this element is fairly straightforward. As illustrated in figure 9.2, the replacement cost should be discounted to the position before the intervention, the difference in value should be assessed and then discounted to the beginning of the planning interval. It is interesting to note that the VRC could be understood as an indirect expression of the fact that there will be an increase in the expenditure necessary to correct defects if they are allowed to develop. An important thing when adopting a short planning interval as proposed in this thesis is to have some mechanism to express the long-term effects that have been truncated. In the model proposed, the long-term effects of a MRI action are not considered because at the end of the planning interval it is assumed that the structure would be rehabilitated and that the cost of this rehabilitation would be proportional to the remaining life of the structure. This is considered as an adequate procedure for strategic analysis of the value of MRI interventions. If the user believes that the variation in MRI expenditure because of condition worsening should be addressed directly, another factor could be included in the model to represent the extra money that would be needed to rehabilitate the element at the end of the planning interval.

9.6 Definition and Use of a Bridge Utility Function

The main reason for investing in maintenance is because it brings benefits. Benefits can be defined as the positive impacts of an action [Hanley at al., 1997]. Achieving a meaningful definition of these impacts in monetary terms is one of the crucial factors in making an accurate economic appraisal of MRI alternatives. This thesis proposes the adoption of an innovative way to assess the impact of MRI actions based on the notion that a benefit (or disbenefit) can be ultimately understood as an increase (or reduction) in utility, as discussed by Hanley & Spash [1993].

Because they increase the chance of failure and impose extra costs in users and the environment, deterioration and inadequacies will reduce utility. Conversely, MRI interventions will improve utility by increasing the possibility of survival and reducing the disbenefits forced upon users and the environment. To determine the monetary expression of the change in bridge utility caused of a MRI intervention to be used in the appraisal model it is necessary to define a Bridge Utility Function. This function should express how the utility varies with changes in the condition of structure. Appendix II discusses how such a function could be structured based on the results of the knowledge elicitation exercises conducted with experts and taking into consideration the discussions carried out in chapter 4. It proposes that the utility of a bridge could be suitably expressed by the aggregation of the following factors: Structural Soundness (SS), Functional Importance (FI), Strategic Importance (SI), Environmental Impact (EI) and Historical Importance (HI):

$$BU = w_s SS + w_f FI + w_{st} SI + w_e EI + w_h HI \qquad \text{(Eq. 9.9)}$$

More factors could be added to the equation if desired, but the ones represented above cover all the relevant aspects elicited from the group of experts interviewed and are seen as a fair expression of the various aspects that determine the usefulness attributed by society to a certain bridge. While some of these components are subjective and cannot be precisely determined, all of them play some part in the decision-making process and can influence the decisions taken. This thesis considers that advanced systems should be able to cope with them if prompted by the user and therefore the utility function proposed should encompass all these different dimensions.

As indicated by the presence of the weight factors in equation 9.9, the user could give a different importance to each of the different utility components. The author investigated how the group of experts would value these different utility components. The results, translated in numeric values using the reference scale of linguistic terms proposed in chapter 8, are presented in table 9.3.

Table 9.3 - Relative weight of bridge utility components as indicated by various sources

Structural / Safety	Strategic	Functional	Historic	Environmental
Extremely high (0.919)	Very High (0.859)	High (0.804)	High (0.804)	Medium (0.517)

Having established how to represent the bridge utility, it is necessary to discuss how variations in utility due to MRI interventions will be estimate, as follows.

9.6.1 Variations in Utility

The value of the components of bridge utility can vary over time due to changes in the characteristics of the bridge or on its role in the network. For example, if a new crossing over a river is created near an old crossing, the strategic importance of the existing bridge will probably be affected. These types of change do not depend on bridge deterioration or MRI operations and will therefore not be significant for the purposes of this thesis. The main factor that affects the bridge utility and is relevant to this work is the change in Condition State of the bridge elements.

A bridge in perfect condition would be at the maximum utility given its current role while deterioration or inadequacies would introduce negative effects and detract from the utility since bridge deterioration can have various undesirable consequences. Structural problems can lead to an increase in the risk of collapse while the deterioration of the carriageway can affect the level of service and the development of substandard conditions might force authorities to restrict access to the structure, for example. The compromise of either the functional or the structural performance of the bridge express itself through several deleterious effects that range from increased congestion to higher emissions of pollutants and increased personal risk to users. Inadequacies in the structure can cause similar problems with an increase in the risk of accidents or the need to restrict access to the bridge.

The various consequences can be reduced to certain basic effects: time losses, increase in accidents, more emissions, loss of the bridge and additional travel expenses. These in turn can be associated with each of the utility components, which will be the result of the monetary expression of these basic factors. For example, the structural soundness can be modelled as the financial value of the structure at risk, which is represented by the Asset Value (AV) multiplied by the variation of the probability of survival in the interval, minus the potential user cost at collapse (UCC):

$$\Delta BU_{SS} = \Delta P_{surv} * AV - \Delta UCC \qquad \text{(Eq. 9.10)}$$

The functional importance meanwhile will be the result of the functional value (FV) at risk minus the variation in user costs (UC) during the interval of the analysis (t_1-t_0):

$$\Delta BU_{FR} = \Delta P_{surv} * FV - \Delta UC(t1\text{-}t0) \qquad \text{(Eq. 9.11)}$$

The historic and strategic components will be an expression of the historic and strategic values at risk:

$$\Delta BU_{HI} = \Delta P_{surv} * HV \qquad \text{(Eq. 9.12)}$$

$$\Delta BU_{SI} = \Delta P_{surv} * SV \qquad \text{(Eq. 9.13)}$$

Finally, the environmental impact component will be:

$$\Delta BU_{EI} = \Sigma^{n}[\Delta R_{emm}(n) * C_{emm}(n)] + \Delta N_{emm} * C_{nemm} \qquad \text{(Eq. 9.14)}$$

where $\Delta R_{emm}(n)$ is the variation the rate of atmospheric emission n, C_{emm} is the monetary expression of the effect of that emission in the welfare of society, ΔN_{emm} is the variation in noise emission and C_{nemm} is the monetary expression of the society willingness to reduce noise emission.

If there is no detailed data about each of its components, the environmental impact could also be expressed as a generic variation in environmental quality (ΔEQ) multiplied by a certain monetary coefficient that express the willingness to pay to avoid the generic degradation in environmental quality (C_{ED}):

$$\Delta BU_{EI} = \Delta EQ * C_{ED} \qquad \text{(Eq. 9.15)}$$

Considering the factors above, the variation in bridge utility ΔBU could be defined as:

$$\Delta BU = w_{SS}[\Delta P_{surv} * AV - \Delta UCC] + w_{FI}[\Delta P_{surv} * FV - (\Delta UC)] + w_{ST}[\Delta P_{surv} * SV] + w_{EI}[-(\Delta EQ * EC)] + w_{HI}[\Delta P_{surv} * HV] \qquad \text{(Eq. 9.16)}$$

Reorganising the elements of the equation:

$$\Delta BU = \Delta P_{surv}[w_{SS} * AV + w_{FI} * FV + w_{ST} * SV + w_{HI} * HV] - [w_{SS} * \Delta UCC + w_{FI}\,\Delta UC + w_{EI} * \Delta EQ * EC] \qquad \text{(Eq. 9.17)}$$

The variation in utility could therefore be seen as consisting of the intrinsic value at risk of the bridge less the sum of negative effects affecting its role. If the sum of negative effects is represented by a factor designated as disutility D, the net variation in utility of a bridge in Condition State CS_0 (at time t_0) at any point t in time to condition State CSn at time tn could be modelled as:

$$\Delta BU_x(t_0,t_n) = \Sigma_t[\Delta P_{surv}(CS_t) * BV_x(t) - \Delta D_x(CS_t)] \qquad \text{(Eq. 9.18)}$$

It is necessary to forecast the Condition State at time t and then calculate the Bridge Value and the Disutility at that moment and in those conditions. The total variation in utility will be the sum of the variations for each period of time t (which will normally correspond to the time between transitions in condition state). The Bridge Value is multiplied by the probability of survival P_{surv} to express the fact that the utility will depend upon the continued existence of the bridge. This formulation implies that, if the bridge fail, the utility is immediately reduced to a value equal or minor than zero, which is considered adequate. The following items discuss how each of the elements of equation 9.18 is going to be calculated.

9.6.2 Determination of the Probability of Survival

The probability of survival P_{surv} is an expression of the uncertainty about the safety of the bridge. Since the probability of survival can be understood as 1- P_{fail}, to determine P_{surv} it is necessary to define how P_{fail} varies with the deterioration of the condition of the bridge. The first step to define this relationship is to recognise that even bridges in perfect condition have a small chance of failure. This chance grows with the worsening of the condition of the structure. Since it has been advocated that advanced systems should adopt a probabilistic approach for condition forecast, the Condition State at time t will not be certainly known, but will be expressed by a vector of probabilities, as discussed in 9.3.4. In these circumstances, the probability of failure could be calculated by multiplying the probability of a element being in a certain state by the standard risk of failure that would be associated with that state. If Rf(x) is the risk of failure for an element in condition state x and CS(k,t) is the probability of the element being in state k at time t, then the probability of failure at time t would be:

$$P_{fail}(t) = Rf(1)^* CS(1,t) + Rf(2)^*CS(2,t) + Rf(3)^*CS(3,t) + Rf(4)^*CS(4,t) + Rf(5)^*CS(5,t) + Rf(f)^*CS(F,t) \qquad \text{(Eq. 9.19)}$$

The risk of failure for an element in failed state should obviously be 1 while the risk of failure for an element in perfect condition (CS=1) should be 10^{-8} according to opinions elicited from experts. The evolution of risk between these two extremes is not clear because there is not a clear relationship between condition states and the probability of failure in existing systems. A particular risk function to estimate these values will be suggested in chapter 10. To transform the risk of an element into a risk to the structure it is also necessary to estimate the structural importance of the element, as discussed by Gastal et al. [1996]. Appendix II contains the results of the determination of expert opinions on this topic.

9.6.3 Determination of Bridge Value

As seen in equation 9.15, four value components have been suggested. The first is the functional value, which can be represented by the asset value as discussed before. There is also the historical value that will depend on the age and uniqueness of the structure and the functional value, which will be associated with the number of users and the type and size of the structure. Finally, there is the strategic value that will be determined by the position of the bridge in the network. It is interesting to notice that the strategic value was established as a result of the examination of expert behaviour and have not been previously discussed in chapter 4.

Attempts to estimate the value components directly could be made but considering that this is a complicated exercise and that a large degree of precision is not deemed necessary for the type of decisions being taken, the author proposes the adoption of a simpler approach. As seen in appendix II, this would consist in the definition of value components as a function of the Asset Value (AV), as follows:

$$V(X)= v_h AV \qquad \text{(Eq.9.20)}$$

Where V(x) is the x component of bridge value and v_h is the majoring factor due to the relevance of the bridge in relation to that factor.

This would mean that equation 9.16 could be rewritten as:

$$\Delta BU = w_{SS}[\Delta P_{surv} \bullet AV - \Delta UCC] + w_{FI}[\Delta P_{surv} \bullet (v_{FI} \bullet FR) - (\Delta UC)] + w_{ST}[\Delta P_{surv} \bullet (v_{st} \bullet STR)] + w_{EI}[-(\Delta EQ \bullet EC)] + w_{HI}[\Delta P_{surv} \bullet (v_{HI} \bullet HR)] \qquad \text{(Eq. 9.21)}$$

Where: w_{ss} is the relative weight given to the structural soundness; P_{surv} is the probability of survival, $_{fail}$). AV is the Asset Value; ΔUCC is the variation in the potential user cost in the case of collapse; w_{fp} is the relative weight given to the functional importance; v_{FI} is the majoring coefficient for functional importance, FR is the functional relevance, ΔUC is variation in user cost, w_{ST} is the relative weight given to the strategic importance, v_{ST} is the majoring coefficient for functional importance; STR is the strategic relevance; w_{EI} is the relative weight given to the environmental impact, ΔEQ is the variation in environmental quality, EC is the monetary cost of the unitary variation in environmental quality; w_{HI} is the relative weight given to the historic importance, v_{HI} is the majoring coefficient for historical importance and HR is the historical relevance.

The set of majoring factors for each condition was estimated using valuation methods such as Revealed Preference, as discussed in Appendix II. Even if these values are just rough approximations, it is recommended that they should be considered in the model. As emphasised by Brent [1996], there is nothing "scientific" about making value judgements implicitly. To comply with the principle of clarity it is necessary to make the system of values that is guiding the decision-making process very clear. This allows all parties involved to understand how decisions are being reached and discuss the validity of the value judgements made.

To use the majoring factors it is necessary to determine the relevance of the structure in relation to each value aspect. An advanced system would have to be able to estimate this information or request it from the user. However, while the historic and functional relevance can be calculated from the characteristics of the bridge or instinctively estimated by the user, the strategic relevance is not so easy to assess. Since the strategic relevance is one of the most important elements of bridge utility, according to the experts, the author has developed a special model to express the strategic relevance that is described in Appendix II and will be validated in chapter 11.

9.6.4 Estimation of Disutility

There are three main disutility components: User Costs (UC), Environmental Cost (EC) and User cost at Collapse (UCC). To implement the appraisal model the variations of each one of them due to changes in bridge condition will have to be modelled. The UCC can be taken as the sum of the potential monetary costs in terms of loss of lives and material damages in case of a possible accident. Considering the average number of vehicles in the bridge (Nv) and using standard values for the average cost of material damages (Cmd) and the cost of a human life (Clife), the variation in the user cost at collapse would be represented by:

$$\Delta UCC = (\Delta P_{fail} * N_v * C_{md}) + (\Delta P_{fail} * P_{ll} * N_v * AVO * C_{Life}) \qquad \text{(Eq. 9.22)}$$

Where AVO is the average vehicle occupancy and P_{ll} is the probability of loss of lives.

To exemplify how this could be used in practice consider a bridge that can carry on average 15 cars. Assume that the AVO is 2.1, the probability of loss of life in the case of an accident is 25%, the monetary cost of a life is £1M and the average cost of material damages is £5,000. In these conditions a reduction in the probability of failure of 0.1% would entail a UCC of £7,950, with the likely material costs representing £75 and the potential loss of lives £7,875. If the asset value were taken as £2M the increase in utility due to structural soundness would be £9,950, according to equation 9.9.

Similar models could be constructed for the other disutility components. The determination of user costs will involve the calculation of the monetary expressions of time losses, increases in the risk of accidents and vehicle operating costs. As discussed in chapter 5, there are various models of different complexity proposed to estimate these values. None of them is precise and the values obtained for the other elements are sometimes subjected to contention, as indicated by Robinson [1993]. But the reasoning exercise demonstrated that experts take them into consideration. Therefore, despite the difficulties in assessing with precision these values it is considered vital to produce a model that include them and allows an estimate of their values if a social decision-making is to be enforced. Even if the values are not precise ones, they will have a great strategic importance and, by making explicit, the model will stimulate the discussion and refinement.

Having this in mind these considerations, an approximate method to calculate them will be proposed in chapter 10 to allow the implementation of the appraisal model being proposed in this chapter. The discussion about what is the best method to calculate precisely each of the disutility components is however beyond the scope of this thesis. The decision about which model to adopt must ultimately come from the user. The majority of models will require the use of local data or the customisation of the original data and methods to match the conditions prevalent in the portion of the network under the responsibility of the authority and therefore no standard approach can be established. The interest of this work is to analyse how, having produced an estimate of these values, it would be possible to use them to determine which would be the MRI strategy that would maximise the "value" obtainable given a certain budget.

9.7 Improvements in the Assessment of the MRI Expenditure

This thesis considers that to make a proper determination of the probable expenditure incurred when a certain MRI action is undertaken to solve a particular problem in a specific bridge it is necessary to modify the current practice of using unit costs as the basis of calculation. As pointed out by Vassie [1997a], the standard unitary values sometimes used to calculate agency expenditure are inadequate to be applied indiscriminately because the real expenditure can vary significantly depending on the physical and functional characteristics of the bridge. The possibility of using a new classification of the expenditure to help overcome this problem is discussed in this section.

9.7.1 Justification of the need for Improvement

Various factors can influence the amount of money spent during the execution of a MRI activity. Some are related to the nature of the activity being carried out while others depend more on the characteristics and the importance of the structure subjected to the activity. Each bridge presents specific problems and difficulties that need to be taken into account. To execute the change of a bearing located on the top of a short pillar on an urban bridge would cost much less than to do the same in a bridge located in a rural spot where the columns are very high and the access is difficult, for example. In the later case it would be necessary to set-up a construction site in a remote location, overcome the access limitations and use special equipment to reach the top of the pillar. All these factors have a direct or indirect (in the sense of a reduction in productivity) impact on the cost.

Special access schemes may also be necessary if the bridge is located over a difficult or inaccessible spot. The importance of this kind of problem can be gauged by noting that 85% of bridges in the U.S. are over waterways [Siccardi & Montoya, 1993]. The expenditure with special schemes for access (such as enclosures) or with specialised equipment (platforms and other plant) can, in some cases, be greater than the cost of performing the activity. Even in bridges where access is not a problem, the expenditure can be much higher than the simple cost of performing the activity. MRI interventions such as joint repairs and pavement overlays that are insensitive to the height of the bridge are however prone to cause serious disruptions to the traffic flow on the bridge. This may have serious consequences, especially if the bridge carries an important road and there are few other possible ways to transpose the natural obstacle that forced the bridge to be erected on that spot.

The cost can also be high if it is necessary to close or restrict the entire carriageway below the bridge to execute the work. Even if access is not a problem, equipment such as suspending scaffolding is frequently used in these cases, at a large expense, to avoid disturbing the traffic on the road below the bridge. Significant amounts of money are usually spent in traffic management when the roads on or under the bridge are heavily congested while structures carrying roads with low ADT and no access problems might still demand a considerable expenditure if they carry a lot of services that need to be removed and replaced.

Because of the influence of these various factors, the use of average unit costs is very inadequate. The adoption of a new structure for representing the MRI expenditure is considered below. It is expected that this new structure will help users understand how the relationships between the physical and functional characteristics of the bridge and the cost of maintenance are formed. This will allow a more representative and accurate cost evaluation to be carried out to supply the values for the appraisal model proposed.

9.7.2 A New Classification for Agency Expenditure

The inspiration for the new classification of agency expenditure came from the notion that it is adequate to isolate the main expenditure from the right-of-way mobilisation and other costs less directly associated with the work. Authors such as Turner and Richardson [1993] have already advocated this idea but it has not yet been implemented consistently. This work considers that the effective use of this approach can be an important step towards producing a more accurate representation of costs and therefore this topic was investigated.

By extending the concept of direct and indirect costs discussed by White et al [1998] to the road environment and considering that there are costs that have intermediary characteristics between these two extremes, a classification consisting of Direct, Related and Indirect costs was created. Overhead costs were not considered because they are incurred by the organisation as a whole and this expenditure cannot be associated with the fact that a particular intervention has taken place. The direct cost is the basic cost of performing the activity. It will depend just on the type of activity being performed and the element affected. The related cost is composed by the costs incurred to support the execution of the MRI activity in a particular bridge. It will include the expenditure with things such as providing special access equipment to allow the activity to be undertaken and establishing temporary light and water connections. Finally, the indirect cost can be understood as the cost incurred to make the work on the bridge viable. It includes expenditures with environmental protection, traffic management and other disturbance minimisation measures.

9.7.3 Direct, Related and Indirect Costs

Being by definition insensitive to the shape, location or importance of the structure, the Direct Cost will be influenced just by the characteristics of the action being considered, by the type of element on which the activity will be performed and by the amount of work required (Q). It would therefore be possible to establish a standard unitary cost (SUC) for each maintenance action and the DC would then be the result of multiplying this unitary cost by the number of units to be repaired:

$$DC = SUC * Q \qquad \text{(Eq. 9.23)}$$

The SUC represents the average expenditure necessary to undertake one unit of the MRI activity given normal productivity conditions and could be developed as a composition, as used in traditional cost estimating methods. A unitary cost per square meter could be defined for painting a concrete element with a certain type of coating, no matter the bridge location, type or overall geometry, for example. The generic nature of this factor is an important characteristic because it allows comparison between values obtained from different sources and facilitates research aimed at defining a standard value for these costs. The value may have to be adjusted to take into consideration conditions that would change the productivity but are not-bridge-specific, such as if the surface to be painted is vertical or horizontal.

The related cost has a close relationship to the type of activity being performed and will therefore be partially dependent on the amount of work being carried out but will also be influenced by the characteristics of the bridge. The most common related cost is the access cost, which is composed by the expenditure incurred to provide vertical or horizontal access to the bridge.

To calculate the access cost, information about the available plant and the bridge physical characteristics is used to check which kind of access equipment would be necessary. The related cost would then be the sum of installing or procuring the equipment plus the cost of operating the equipment plus the increase in the cost of performing the activity due to the reduction in productivity caused by the use of the equipment. To appropriate the related costs a linear model consisting of two parcels was therefore proposed:

$$RC = \alpha + \beta * Q \qquad \text{(Eq 9.24)}$$

The first parcel (α) will be a lump sum representing the expenditure incurred to set-up the support for the MRI activity. The second parcel (β) is formed by the unitary cost of operating the support equipment plus the extra expenditure due to the reduction in productivity caused by the use of the equipment, as follows:

$$\beta = UOC(Equipment) + RP * \%L * SUC(Activity) \qquad \text{(Eq. 9.25)}$$

where UOC is the unitary operating cost, RP is a factor that represents the reduction in productivity and %L is the percentage of the standard unitary cost attribute to labour.

Table 9.4 – Detailed Structure Proposed for the Agency Expenditure

Cost	Examples		Format
DIRECT	• Material Cost + Man Hours	--	SUC * Q
RELATED	• Access Equipment	Physical	$\alpha + \beta * Q$
	• Disposal rubble/Waste	Locational	
	• Provision Power/Water	Locational	
	• Red. Prod. due to Work Method	Functional	
INDIRECT	• Removal/ Reposition of Services	Functional	$\chi + \delta * T$
	• Setting-Up Costs	Physical / Locational	
	• Temporary Access Schemes	Physical	
	• Environmental Protection	Locational	
	• Traffic Management	Functional	
	• Possession Payments	Functional	

Indirect Costs will be represented by a Lump Sum but can also have a time–dependent component. For example, the expenditure with traffic management can consist of an initial cost of installing the signalling system plus a time-dependent value of operating it. Indirect costs will therefore have a similar structure as the related costs. Table 9.4 shows the generic format of each of the three types of costs and presents the main examples of each of them.

9.8 SUMMARY

This chapter discussed some initiatives for developing an improved appraisal model for use in advanced systems. The model proposed goes beyond current practice by considering the opportunity cost and the external impacts of MRI interventions and making allowances for the impact of different strategies in the service life expectancy. To support the new model an innovative way of assessing the impact of changes in the Condition State of a structure was developed based on the concept of Bridge Utility. A utility function that would take into consideration not just user costs but also the historical and strategic importance and the environmental impact was discussed. The inadequacy of using standard unitary costs to estimate the agency expenditure was also discussed and a new classification of costs was proposed. Until now, few real attempts have been made at evaluating the large portion of costs and benefits that is not directly quantifiable in monetary terms. Because of this, MRI strategies were often decided based just on the compliance to standards and the analysis of benefits was reduced to the ones brought to users by reducing accidents. The results obtained were therefore bound to be of limited usefulness. The author believes that, by addressing some of the inadequacies of existing practice and enlarging the scope of impacts considered, the new appraisal procedure provides a better basis for the selection of MRI strategies based on a social view of the process of Bridge Management. Chapter 10 will demonstrate how this theoretical basis could be implemented in practice.

Chapter 10

Development of the Appraisal Sub-System of an Advanced System

10.1 INTRODUCTION

The present chapter examines how the concept of a new economic appraisal model proposed in chapter 9 could be fitted together with the novel architecture discussed in chapter 8. The author's aim is to demonstrate that the procedural and technical improvements suggested in this thesis form a coherent blueprint for the production of advanced systems. The discussion will initiate with an overview of a generic system denominated ORIGAMI, explaining how the appraisal sub-system that will be developed in this chapter would be connected into a wider structure. The chapter then focuses in the examination of the object model and the basic structure of the appraisal sub-system proper.

10.2 THE ORIGAMI CONCEPT

This chapter discusses the development of certain elements of a demonstration version of an ABMS that will be denominated ORIGAMI. The acronym stands for **O**pen Architecture, Flexible **R**easoning, **I**mproved Appraisal, **G**eo-referenced, **A**dvanced Bridge **M**anagement **I**ntegrated system.

According to the framework proposed in chapter 7 and refined in chapters 8 and 9, object orientation will be used in the construction of the ORIGAMI system to produce an open architecture. The system will also have a GIS component and employ Fuzzy

Logic to add flexibility and simulate an intelligence behaviour trough soft reasoning with natural language variables. Additionally, the ORIGAMI system will adopt the new appraisal model proposed by the author, which is suitable to support VFM policies and uses the notion of bridge utility to shift the focus of the analysis to adopt a social view of the problem.

10.2.1 Basic Structure

Figure 10.1 shows part of the uppermost level of object model proposed for the ORIGAMI system. A complete model should contain procedural objects representing each of the activities discussed in chapter 2 since to make ORIGAMI into a fully operational Advanced Bridge Management System it would be necessary to develop all these components. However, since the focus of this thesis has been the step of therapy definition, just this part of the system's structure is shown in the diagram.

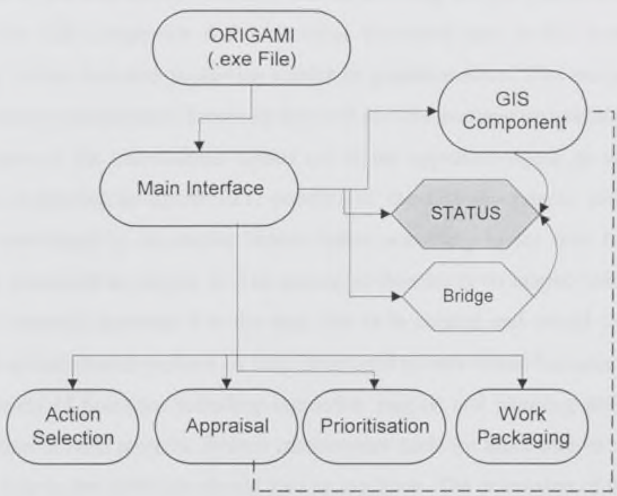

Figure 10.1 – Uppermost Level of the Structure of the ORIGAMI system.

10.2.2 System Initialisation

As illustrated in figure 10.1, a small executable file is used to initiate the ORIGAMI system. This file has two basic tasks: controlling accesses (via password and user identification) and creating the root object that will be the core of the system. The root object will be the *Main Interface* because, following the idea that an advanced system should be user–oriented, the first step when the software is activated is to establish a means of interaction with the user. The *Main Interface* is in charge of monitoring the interface with the user and translating commands into instructions to the rest of the program. It does this by controlling the creation of the objects necessary to perform the various analyses and managing their order of activation. It would have been possible to fuse the Main Interface with the initial executable program. The author decided against this idea because this would imply that no other object created would be able to activate procedures inside the Main Interface. By making the main interface as an object and passing a pointer to it to other objects the system becomes more flexible.

The earliest object created by the Main Interface is the *GIS component*. The reason for this is that this approach allows the user to use a spatially oriented interface (a digital map) to communicate with the system. The spatial interface establishes natural ways for the user to perform certain functions such as selecting bridges that he has interest in analyse. The GIS component will have other important uses at this level, such as displaying bridge data and presenting results in graphical form. This component will also have more sophisticated functions that will involve performing spatial analyses to support some of the calculations carried out in the appraisal object, as will be seen ahead. As suggested in figure 10.1, pointers to the *GIS component* and the *Main Interface* are stored in the carrier object *Status*, according to the data transmission procedure discussed in chapter 8. The system is then ready to interact with the user. From this moment onwards it is the user that is in control and would chose which action the system should perform. A fully developed system would be expected to offer a wide variety of functions including inspection support and planning and control of the execution of MRI projects. System maintenance tools for tasks such as updating or inputting data in the databases should also be available. The discussion of the majority of these activities will not be of interest at this point. The main function of a BMS, as discussed in chapter 3, is to provide assistance in the decision-making procedures involved in establishing a MRI programme. The examination of its functions will therefore be restricted just to the ones directly related to this aspect, as seen below.

10.2.3 Dynamics of Decision-Making in ORIGAMI

The first important step in terms of decision-making would consist in the definition of the set of bridges to be analysed. Because of the capabilities of ORIGAMI, the user could choose to select the set graphically, using the GIS interface available in a special window, or trough queries created with the traditional menu-driven windows-based interface. The possibility of creating a *Bridge* object for each bridge marked for analysis was considered. However, this approach could result in the need for a significant amount of memory space if the set of bridges is large. It was therefore decided that just one bridge object should be created and that the record of the bridges to be analysed should initially be maintained as a vector in the *Main Interface*. When the analysis is initiated the active or current bridge is established and the data concerning it loaded from the respective databases into the *Bridge* object. A pointer to it is then passed to the *Status* object from where the other objects will have access to it. The analysis is carried out sequentially for each bridge in the selected set.

Having defined the active bridge the next necessary thing to do is to retrieve the data about the elements that compose it. If a strict procedure were followed, it would be necessary to check the various bridge defects existing in each bridge element, determine their isolated and combined effects and use this information to produce a matrix of Condition States (CS) for that element. It will be assumed however that this was done when the data was entered in the system or that the data has already been collected in the form of CS grades. It will also be assumed that the verification of compliance, the condition forecast and the risk assessment steps have likewise already been undertaken and that data about the transition probabilities and the current risk of collapse of the bridge is also known. With this data in hand, the *Action Selection* object determines the suitable alternatives for intervention in a bridge. This object creates a set of possible MRI strategies by examining various possible courses of action to solve the existing defects. These strategies could be automatically generated or defined by the user. Having established the strategies to consider and considered their effects on the Condition State of the element, the *Appraisal* object is then activated. This object uses the information calculated by the various preceding POs, combining and reprocessing it to determine the value index for a particular MRI strategy in a certain bridge element. This narrow focus of analysis (element by element) was considered necessary because the new procedures being introduced demand that data about each element should be considered in separate, since the expenditure is taken as being associated with the particular characteristics of that element.

The identification of the preferred course of action to adopt for a certain element is done by cross-checking the value indexes of the various possible strategies. The problem is that, in practice, authorities rarely act upon a single element in a bridge (although it could happen in the case of accidents). They are prone to correct various elements at the same time because this usually results in an economy of scale due to optimisation of the use of resources and the reduction of disruption by the overlapping of activities. The ORIGAMI system deals with the problem by using the concept of projects. The strategy for each individual element will give origin to what will be denominated as a Single Activity Project (SAP). Data about the maintenance expenditure and other specific results of the appraisal will be stored by project. The concept of Combo projects allows the system to expand the analysis to the whole bridge. A Combo project is a virtual collection of single activity projects. To form it the value index of the various individual projects is aggregated, with special procedures used to calculate the reduction in expenditure and in the external costs due to the optimisation of resources or the reduction of disruption originating from the simultaneous execution of the activities. A Combo project will be adopted if there is an increase in the Value Index when the single projects are combined. Alternatively single and combo projects could be allowed to compete with each other during the prioritisation but the adoption of a combo project would automatically exclude all the single projects agglutinated to form it.

Because of the specific structure of the appraisal discussed above, one of the most important features of the ORIGAMI system is the need for a reliable *Work Packaging* object. Work packaging is already present in a rough format is some existing systems, as discussed in chapter 2, but this thesis believes that it is necessary to give much more emphasis to this topic. This author considers that it would be necessary to construct intelligent aggregation routines and allow a greater input from the user in this sense. Apart from the traditional type of combo project that is composed of various activities performed in a particular bridge, other types of combo projects could also be envisioned. It might be useful for example to co-ordinate works in bridges close to each other in order to avoid the duplication of disruption and the consequent rise in user dissatisfaction. Combo projects could also be formed by selecting certain types of activity that must be performed in various bridges at the same type. This would usually involve preventive regular maintenance activities as painting or cleaning.

The list of aggregated projects resulting from the application of work-packaging is used to feed the *Priori'isation* object, which has the function of distributing the budget alongside the network. The standard method for prioritisation used in ORIGAMI consists of a linear model that finds the portfolio of projects that maximise Value for Money. After defining the MRI strategy and the priorities for the whole network, it is still necessary to determine how the works will be organised temporally, establishing a co-ordinated MRI programme. The time of the year can have an impact on the MRI expenditure because of seasonal factors affecting the possibility of working or the level of traffic. It is necessary therefore to perform an analysis to take into account these factors and produce an adjusted Value Index. The ORIGAMI system will have a *Programming* object that can perform these functions.

This section discussed the ORIGAMI system from a general perspective to give a sense of how the system as a whole is expected to work and illustrate how the establishment of MRI programmes is expected to occur in an advanced system. However, as discussed before, just the *Appraisal* object will be fully developed in this thesis, because it is the one that encapsulates the changes proposed in previous chapters and will be primarily responsible by the innovative nature of an ABMS.

10.3 IMPLEMENTATION OF THE APPRAISAL SUB-SYSTEM

An object model is proposed in figure 10.1 to represent the appraisal sub-system. It is important to highlight however that the examination will be restricted to carry out an object-oriented analysis (OOA) of the problem. As described by Khoshafian and Abnous [1995], an OOA consists in describing a system using object notation, concepts and methodology while object oriented design (OOD) aim to give a more detailed blueprint for implementation, which goes beyond the scope of this work.

The object model proposed is based on the decomposition of the theoretical model proposed in chapter 9, which is represented by the *Value Index* object. As indicated in the diagram, the undertaking of the appraisal using this approach could be just one of the options included in the ORIGAMI system. The principle of flexibility implies that it would be possible to have alternative objects for undertaking other types of appraisal based on other techniques. However, as pointed out along this thesis, there is good reason to base the optimisation process on a social cost-benefit analysis and the Value Index model provides a sound basis for such an approach.

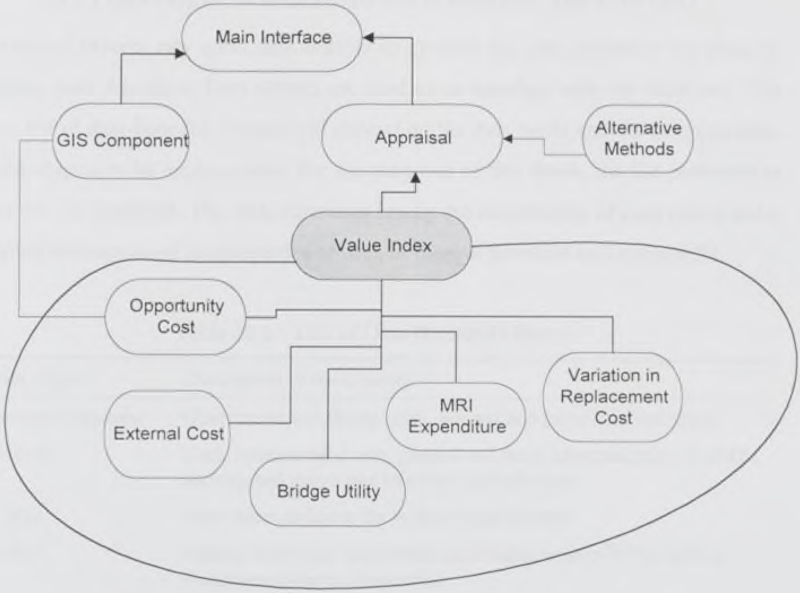

Figure 10.2 – Initial decomposition of the appraisal object model.

Each of the objects shown in the diagram as composing the *Value Index* (*Opportunity Cost, External Cost, Bridge Utility, MRI expenditure and Valuation in Replacement Cost*) activates other objects and combine their results to provide an answer when activated. Before the composition of these objects is discussed one question that must be posed is how much should the model be refined. It would be possible to establish a considerable number of objects. However, after some stage further decompositions are not productive because objects become too simple and numerous. The author tried to balance the need for flexibility with the creation of a relatively simple structure. The five primary objects will activate other fourteen procedural objects. Details about the structure of each of the various objects comprising the model is briefly discussed in Appendix IV. Due to the flexible architecture implemented in ORIGAMI, modifications could be introduced easily if desired by users and developers. It is expected that in time new objects will replace or complement the ones suggested in this work.

10.3.1 Data Objects Suggested for Supporting the Appraisal

Procedural objects rely upon data objects to provide the data necessary for them to perform their functions. Data objects are used as an interface with the databases. The exact list of data-bounded objects will depend on the data needs and the characteristics of the objects to be implemented. For the purposes of this thesis, the list presented in table 10.1 is proposed. The table discusses briefly the constitution of each object and a detailed description of the properties of each of them is provided in Appendix III.

Table 10.1 – List of Data Bounded Objects.

Data Object	Description of the Content
Access Equipment	Operational and set-up costs, general and fuzzy characteristics
Activity	Cost, measurement unit, general and fuzzy characteristics of a MRI activity and associated transition probabilities.
Bridge	Parameters defining the bridge characteristics
Defect	Nature, extension, importance and characteristics of the defects encountered during inspection
Element (Column, Joint, Bearing, etc.)	Characteristics of the element where the defect is located.
Policy	List of the relative importance given to the various decision criteria.
Rule	Code, type and characteristics of the antecedents and consequences
Project	Code, type, cost, composing activities, etc.
Link	Average Daily Traffic, detour routes, standard VOC, frequency and cost of accidents, etc.
Work Method	Type, consequences on the traffic flow, cost of implementation, etc.

10.3.2 Dynamics of the Appraisal Sub-System

The appraisal analysis starts with the *Value Index* object being activated and receiving the *Status* object containing the current *Bridge* object. The next step is to create the data objects necessary to support the analysis, such as the *Policy* object. Pointers to these objects are stored in *Status* for general use. Subsequently, the *Value Index* object creates and initialises the five procedural objects that represent the basic elements of the model described in chapter 9. The *Value Index* object then examines the bridge data and creates objects to represent each of the elements of the current bridge. For each element the possible MRI strategies are retrieved and the five procedural objects are run for each pair element:MRI strategy. Value indexes are then calculated for each strategy and the one with the best VFM ratio is defined as the preferred one. The characteristics of the preferred strategy are stored in the Project database together with the results of the analysis. This procedure is repeated for each element. In the end all unnecessary objects are destroyed and control is returned to the *Appraisal* object and from there to the *Main Interface*.

The following sections will present a brief idea of what is the function of each element of the model and discuss how they are expected to operate in ORIGAMI. Special attention will be given to the discussion of the *External Cost*, the *MRI Expenditure and Bridge Utility* objects, because some of the methods used by them and their related objects illustrate how the new architecture is used to support the novel appraisal model.

10.4 The External Cost Object and its Relations

The *External Cost* object is the first one to be activated in a standard run because the information produced by it will be useful in calculations performed by other objects. The *External Cost* has the function of performing a monetary valuation of the impact of MRI interventions on third parties. As discussed in previous chapters, this will imply the determination of effects on users and the environment since the effects on society in general are still difficult to model. As suggested in figure 10.3, two objects were created to represent each of these factors: *User Cost* and *Environmental Impact*. The *External Cost* object activates them, request them to calculate their values and combine the results taking into consideration standing policies and user directives to produce a value to send back to the *Value Index*.

One interesting consideration is that the external cost is closely related to the work method adopted. Another object (*Work Strategy*) will be used to determine which would be the Work Method that would probably be adopted given the current conditions (bridge, MRI activity, policy and element). However, this will just be done later, during the verification of the MRI expenditure. At this point, therefore, the user cost and the environmental impact will be determined for each possible work method.

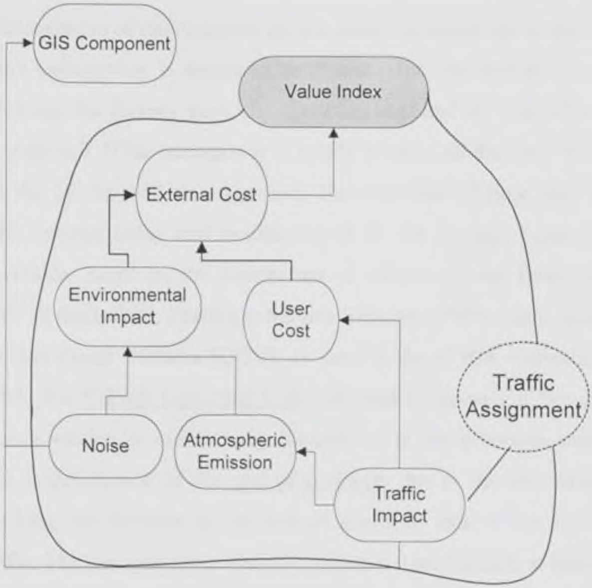

Figure 10.3 – Representation of the relations of the External Cost object.

USER COST OBJECT

The *User Cost* object is in charge of determining the increases in risk and expenditure to which users are exposed at different levels of performance of the bridge. This object could be activated both to calculate the external cost generated by MRI interventions, as is the case here, as well as to check how different MRI strategies affect the bridge utility, as will be discussed in the next section (10.5). Distinct methods will be used in the two situations. In this section the method that calculates the user cost due to interventions, denominated *MRI_Impact,* will be discussed.

As remarked before, the user cost will have to be calculated for each work method. The initial step therefore is to assess the consequences of adopting a certain work method. Then it is necessary to roughly estimate the duration of the work from the characteristics of the activity and the amount of work to be done. With this information and valuations on the monetary importance of the impacts (appendix III presents some discussions about valuation methods and provide some reference values to be used in ORIGAMI) the total value of the impact on the users can be calculated.

The main consequences of interventions for the users are connected to the reduction of the flow if the carriageway is narrowed or closed. This can lead to congestion and detours, increasing the journey time, the operating cost and the risk of accidents, as discussed in chapter 9. If the carriageway is totally blocked all the flow will have to be diverted and the effects will be magnified. The valuation of <u>time loss</u> is made by estimating the average delay and multiplying it by the average value of time per category of vehicle, based on the distribution of vehicles in the flow. Four vehicle categories will be used: Cars, Passenger Service Vehicles (PSV), Light Good Vehicles (LGV) and Other Good Vehicles (OGV), as used in the COBA software in the UK [COBA, 1996]. The <u>Vehicle Operating Cost</u> will tend to increase if the speed trough the maintenance section is reduced significantly or if the diversion route is much lengthier. The determination of the <u>cost of accidents</u> due to the intervention will be done by verifying the increase in the risk of accidents due to the roadworks and increased traffic. The user cost object has to estimate values for each of these impacts.

An advantage found in the conception of this object is that the user cost is the most visible parcel of the external costs and has been the subject of various studies from part of bridge authorities and governments. Since the determination of user costs is not the main contribution of this thesis, the ORIGAMI system could initially be adapted to use the results from other software like QUADRO [DOT, 1982] to estimate the impacts on users. Routines to allow the introduction of this data by the user should therefore be established. However, from a strategic point of view greater consistency of structure and interfaces might be desired and it would be preferable to construct inside ORIGAMI objects that can perform similar tasks using models adapted from QUADRO. This approach should be the preferred solution in the view of the author because QUADRO is a dos-based system and has some serious limitations in terms of data input. The lack of flexibility means that various adjustments had already to be made because of the lack of access to certain parameters.

A mixed solution is proposed for the initial version of the ORIGAMI system. It consists in the creation of procedures to receive and use the information derived from QUADRO but at the same time provide the *User Cost* object with a broader and more sophisticated structure that could organise the available data in a different format, perform new calculations and interpret or extend the results obtained. This approach was considered vital to allow the *User Cost* object to relate properly to the other objects in the model. Following this line of thinking a special object denominated *Traffic Impact* was created to do the connection with QUADRO in the current data structure. This object had the task of estimating the effects of queues and detours due to the interventions. With this information the *User Cost* object could then calculate the value of the various components of the user cost.

TRAFFIC IMPACT OBJECT

The *Traffic Impact* object is an object activated by the User Cost. It is in charge of calculating the effects of the intervention in terms of delays, detours and increase ion risk. To do this the author considers that it is necessary to go beyond current practice and introduce in the system a traffic assignment model. Due to the importance of these results both in the assessment of user costs as well as environmental costs, it is not considered adequate to use simple formulae based on the ADT and detour length as it is done currently. It is necessary to implement a more sophisticated structure that could take into consideration the results of a traffic assignment exercise. The *Traffic Impact* object would act as an interface with the assignment model and interpret the results. The author considers that ORIGAMI could be adapted to communicate or incorporate sophisticate assignment models such as the Saturn [University of Leeds Website, 1996] or even the most traditional QUADRO. While this is not made possible, the manual input of the results or the use of a simplified assignment model based on QUADRO should be considered. To this end a procedure could be developed that calculates the speed-flow relationships for both routes and assume a queue equilibrium in order to verify the impact that the detoured vehicles would have in the alternative route.

The results of the calculations provided by this object include: the length of the detours (for each direction); the speed of flow in them and on the main road during the intervention; the increase in the risk of accidents due to the intervention; and estimates about the percentages of vehicles that are going to be allocated to each route. The *Traffic Impact* object would send them back to the *User Cost* that could then estimate the delays, the VOC and the cost of accidents.

Environmental Impact Object

Similarly to the *User Cost* object, the *Environmental Impact* object will also have a double role, with methods to calculate the impact because of interventions and because of changes in Condition State. This item will discuss the first of these methods (MRI_Impact). It is important to stress that the determination of the effects of MRI strategies in the environment is one of the important modifications deriving from the improved appraisal model proposed in this work. Its use helps to establish a more accurate representation of the system of priorities used by bridge managers to decide which course of action to pursue, as indicated in the knowledge elicitation exercises.

There are various possible environmental impacts to consider, as discussed in chapter 5 and emphasised by Vickridge et al. [1989] and Hanley et al. [1997]. Two of them are considered as suitable to be incorporated at this stage: noise and atmospheric emissions. Beyond being befitting to mathematical modelling and valuation, they are the ones considered more relevant by the Royal Commission on Environmental Pollution [1995]. Specific objects will be used to represent each of them. The role of the *Environmental Impact* object will therefore be to activate these objects and combine their results according to the system of values and weights defined by the user in order to provide a monetary estimation of the impact of the MRI intervention on the environment.

Atmospheric Emission Object

This object provides a monetary valuation of the impact of atmospheric pollution caused by the intervention. Chapter 5 provided some reference values for the monetary cost that can be attributed to various types of emissions. These can be used to estimate the total cost but it is necessary also to determine the variation in emissions due to the intervention. Figure 10.4 provides information about typical emissions for an average car under standard conditions (the MVEG cycle).

As suggested by the equations, for different velocity regimes the consumption would be different. Appendix VII expands the explanations about the emissions model and contains some numerical estimates about the consumption at different conditions. The most difficult one to estimate is the consumption in slow moving intermittent conditions. It is almost impossible to make a precise determination in this case because of the number of variables that intervene in the calculation. According to the literature, however, the consumption in a queue can be considered as approximately equal to four times the normal consumption [Friends of the Earth Homepage, 1998]. This was the value adopted as reference. Alternatively, the value of the fuel consumption could be calculated using the equation 10.6 suggested in QUADRO [DOT, 1982]. The additional amount of fuel consumed due to the intervention would be estimated by dividing the result by the average price of a litre of fuel:

$$C = (a + b/V + c\,V^2)\,(1 + m\,H + n\,H^2) \qquad \text{(Eq. 10.6)}$$

Where V is the speed, H is the average hilliness (total rise and fall per unit distance in m/km) and the rest are parameters for each vehicle category.

Having determined the extra consumption by one of these methods it is possible to estimate the variation in emissions due to the intervention and, using the values discussed in appendix III, associate a monetary value to them. Two calculations have to be made: one for cars and LGVs moved by petrol and other for heavy vehicles using diesel, since the average consumption and the emissions are different in each case.

Noise Object

The Noise object estimates the disturbance caused by noise emissions generated by the intervention and attributes a monetary value to it. As seen in chapter 5, noise is considered a problem because users attribute to it various undesirable consequences, such as hearing loss, stress, high blood pressure, sleep loss, distraction and lost productivity. These effects result in a general reduction in the quality of life and in the opportunities for tranquillity [Noise Pollution Clearinghouse Homepage, 1998]. The recognition of this aversion to high levels of noise subsidises the determination of a certain value to express the willingness to pay (WTP) to avoid or reduce noise, as discussed in appendix III.

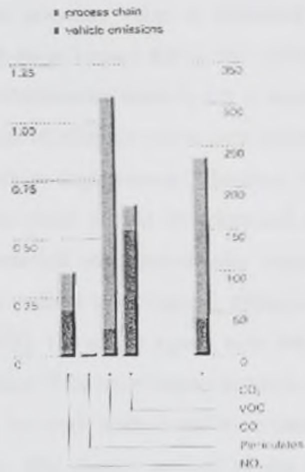

Figure 10.4 – Emissions for petrol in g/km (Source: Volkswagen, 1997).

Assuming this to represent the emission in normal use and considering an average consumption of around 0.15 l/km (equivalent to en economy rate of 6.7 km/l), the average amount of emissions per litre of fuel burned in normal conditions could be roughly estimated. The emissions could then be associated with the fuel consumption. This was the starting point chosen to create the first version of the *Atmospheric Emissions* object.

This thesis proposes that a method should be implemented in the *Atmospheric Emissions* object to estimate how much extra fuel would be consumed during the intervention. Briefly, the variation in fuel consumption (ΔQ_F) could be modelled as:

$$Q_{F0} = D\,(HAHT * AFC(V_0) * L_0) \qquad \text{(Eq. 10.1)}$$

$$Q_{F1} = D\,(\%HAHT_{detour} * AFC(V_{detour}) * L_{detour}) \qquad \text{(Eq. 10.2)}$$

$$Q_{F2} = D\,(\%HAHT_{main} * AFC(V_{main}) * L_{main}) \qquad \text{(Eq. 10.3)}$$

$$Q_{F3} = D\,(\%HAHT_{queue} * AFC_{cong\text{-}stop} * T_{queue}) \qquad \text{(Eq. 10.4)}$$

$$\Delta Q_F = Q_{F0} - (Q_{F1} + Q_{F2} + Q_{F3}) \qquad \text{(Eq. 10.5)}$$

Where D is the duration of the intervention, HAHT is the homogenised average hourly traffic, V is the average speed on the link, L is the length of the link, AFC is the average fuel consumption for an standard traffic unit given a certain ADT matrix and an speed V.

Having defined how the monetary value is attributed to noise it would then be necessary to estimate the noise impact due to the intervention. The FHWA [1995a] however advocates that construction noise is not a major issue. They argue that the public often views this type of noise as a short-term inconvenience and consider it as a necessary price for growth or improvement. Therefore, the FHWA recommends that the highway construction noise should be addressed in a qualitative rather than quantitative manner. If potential construction noise impacts are identified, a common sense approach should be utilised to incorporate appropriate abatement measures into the project [FHWA, 1995b]. The author agrees with this stance and believes that the most important consequence of the noise impact in terms of the MRI intervention is its influence in determining the work method and the consequent effects in terms of the agency expenditure. The *MRI_Impact* method of the *Noise* object will therefore concentrate in estimating the noise sensibility of an area in qualitative terms. The noise sensibility of an area will result from the number of houses affected and the level of exposure and will be expressed using fuzzy variables associated with linguistic terms, such as high, medium and low. The GIS component will be used to help determine the noise sensibility of the area. The author sees this as a natural opportunity for using the spatial analytical capabilities brought by the introduction of this technology in an advanced system. The proposal is to apply a noise dispersion model to estimate noise level isocurves around the bridge. Spatial operators will then be used to define the type and number of places affected beyond the acceptable level. A subjective criterion based on user preferences or standard values will be adopted to transform and aggregate this data to determine the noise sensibility. The simplified dispersion model to be used in the initial version of ORIGAMI is discussed in appendix VII. It is based on the fact that the sound intensity decreases with the square of the distance from the source and will not consider attenuation or reflection.

10.5 THE BRIDGE UTILITY OBJECT AND ITS RELATIONS

The *Bridge Utility* object is used to determine the variation in bridge utility (VBU). It does that based on the results of four other objects: *Bridge Value, Reliability, User Cost and Environmental Impact*, as seen in figure 10.5. The later two were already explained but now will be used to determine the effects of changes in Condition State.

The *Bridge Value* object has the function of determining the total value of a bridge. This information is used to estimate the variation in utility due to the variation in the risk of failure caused by the adoption of the MRI strategy being considered, which is calculated using the *Reliability* object.

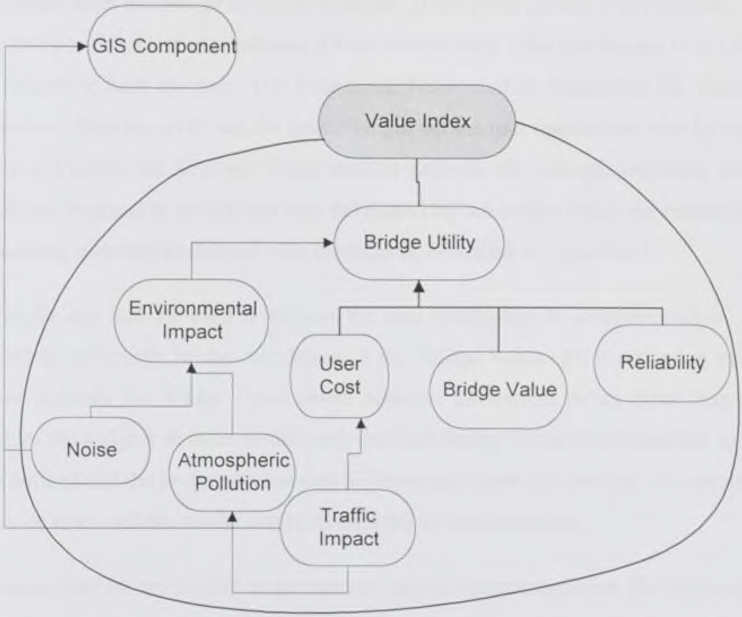

Figure 10.5 – Representation of the relations of the Bridge Utility object.

Bridge Value Object

Following the ideas discussed in chapter 4 and detailed in Appendix II, the total bridge value will be considered as a combination of the Asset Value with the Historic, Functional and Strategic Values. Individual objects could be created to calculate each of these value components. In this way, if a new way to calculate them were defined, it would be possible to just substitute them instead of having to reprogram the general Bridge Value object. This approach would also allow the introduction of more than one way to calculate them if desired. However, in this initial version of ORIGAMI they were designed as internal methods of the *Bridge Value* object.

Each of the value components will be calculated by multiplying the relevance of the bridge in relation to the aspect concerned by a certain differential of value that is associated with that aspect, as discussed in chapter 9. The differentials of importance have been estimated using expert opinion and are described in Appendix II. It is necessary however to establish procedures to calculate the relative relevance of a certain bridge. The *Historic Value* method initially tries to retrieve the historic relevance from the Bridge Inventory database. If this piece of data is not available there are two possible solutions: estimate it from certain basic rules and the age of the bridge or request it from the user. The *Functional Value* method determines the functional relevance from the ADT and the detour length but the user opinion can also be used to alter it. Finally, the *Strategic Value* method estimate the strategic relevance using a Multiple Regression model that was developed by the author using the results of the reasoning exercises performed with the experts, described in Appendix I.

Weights can then be used to express the user willingness to consider each of these elements differently in the calculation of the Bridge Value. After activating each of these methods the *Bridge Value* object retrieves the current policy from *Status* and applies the weights in order to calculate the final Bridge Value. If no standard weights are defined and the program is running in interactive mode the user can be consulted to provide them. All the results can be overridden by user estimates.

Because they do not depend on the specific project being considered, the Strategic and the Historic Value of the bridge are calculated as soon as the *Bridge Value* object is initialised, increasing processing speed by avoiding having to calculate them for each project to be analysed.

RELIABILITY OBJECT

Having determined the Bridge value, to determine the Value at Risk it is necessary to establish a relationship between the variations in the Condition State and the variations in the risk of failure. The *Reliability* Object is in charge of performing this function for the *Bridge Utility* object. Since Single Activity Projects will be used during the appraisal, the *Reliability* object normally determines how the risk to the particular element in consideration will vary with the changes in its condition. But to assess the variation in bridge utility due to a certain MRI alternative it is necessary to determine the effects that changing the condition of that particular element would have on the whole bridge. To calculate this second factor it is necessary to know the risk level of the whole bridge before the change took place. Theoretically this information would already have been calculated during the risk assessment phase using another method of the *Reliability* Object. In this initial version of ORIGAMI the initial (i.e., at t_o before any decision is taken) bridge reliability will be calculated using a serial model that aggregates the risks caused by all elements, taking into consideration the different structural responsibilities of each of them, as suggested by equation 10.7.

$$\beta(\text{bridge}) = \Pi\ [(1-(RF(Ei) * ESR(Ei))] \qquad \text{(Eq. 10.7)}$$

(Where ESR is the elements' structural relevance, Ei represents the ith element of the bridge)

Information about the structural relevance of each element can be found in appendix II. Having calculated the initial bridge reliability, it is possible to estimate how the change in the condition of a particular element affects the whole bridge by substituting the risk of failure for that element in the equation while maintaining the risk of failure for the other elements as constant.

The whole procedure discussed above is based on the determination of the risk of failure of a particular element in a certain Condition State. Unfortunately, these values have not yet been unquestionably defined and there is a lack of structured studies in this topic. PONTIS in a roundabout way derives some values from estimates of remaining lifetimes given by experts (these values can be retrieved from the standard example available with version 2 of the software). In the absence of reliable sources and in order to simplify the calculations it is proposed that, in the first version of ORIGAMI, the *Reliability* object should use a pre-determined risk function to calculate these values. A simplified risk assessment model to fulfil this role is presented and explained in Appendix VII.

User Cost Object

As discussed in chapter 5, bridge deterioration can have various adverse effects on users. If a structurally important element has deteriorated significantly or is structurally obsolete, there might be a need for restriction of traffic or imposition of speed limits. The deterioration of elements less important structurally but that have a direct effect on the flow of traffic (such as pavements or joints) could likewise generate a reduction in speed. These occurrences would lead to detours and congestion, with consequent increases in the user costs. Even if the deterioration is not serious and does not affect the traffic, it might increase other risks, such as the risk of a pedestrian being hit by a falling piece of concrete or a car not being held by the protection barriers and falling into a gully. The deterioration of signalling in urban bridges can also have an adverse effect in terms of the number of accidents.

The user cost has to estimate the effect of these various impacts (detours, delays and increase in the risk of accidents). To determine the user costs originating from the deterioration of the structural condition of the structure it is necessary to determine if any load restrictions that would force the detour of vehicles is in force. This can be done using traditional structural appraisal techniques and will be assumed as an existing data. Knowing the percentage and type of vehicles detoured, this element of the user cost can be calculated with help of the *Traffic Impact* object described earlier.

The estimation of the other components of the user cost due to reduced performance and increased risk resulting from the deterioration or obsolesce of bridge elements is more complicated. The author has not identified reliable ways to consider these factors in the literature. More studies will be necessary to elaborate suitable relationships to be used in the analysis. This is not one of the main interests of the work but to allow the system to consider these factors, and since a great degree of precision was not considered necessary for the strategic decision about the best MRI programme, two approximate models were developed to be used in ORIGAMI until better models become available. They are described in appendix VII with the rest of the models. Nonetheless, if the use of the models is not considered adequate, provisions were made to allow the user to give a direct estimate of the effects of the MRI strategy being considered in terms of accidents and functional disturbance

After applying the models and calculating the various components of the user cost, each of them is multiplied by a relative weight defined by the user. This generally express the different importance given to each of them and it is useful if the user does not want to consider these factors because he can turn the relative importance of a component to zero therefore in practical terms avoiding its consideration in the analysis.

Environmental Impact Object

The *CSChange_Impact* method of the *Environmental Impact* object is used to calculate the environmental costs deriving from changes in the Condition State of a bridge element due to deterioration or MRI actions. As discussed before, the two main environmental impacts that will be considered are atmospheric emissions and noise and an object represents each. Each will therefore have a corresponding *CSChange_Impact* method.

Atmospheric Emission Object

Changes in Condition State impact the atmospheric emissions because, as discussed above, they can originate variations in the average speed or in the length of the journey. The lifting of weight restrictions due to maintenance will reduce the journey length and the journey time for heavy vehicles, hence reducing fuel consumption. Emissions can also be affected if the road is upgraded or enlarged, leading to higher ADTs and different speed regimes. A verification of alterations in detour needs and speed should therefore be carried out for each change in Condition State. Specific circumstances could be taken into consideration by using rules.

Noise Impact Object

It is very difficult to associate the deterioration of elements with changes in noise emission. This factor will therefore not be considered unless it refers to improvements that would effectively reduce noise, like the erection of noise barriers or the enlargement or upgrading of the road. In these cases the recommendations from the FHWA [1995b] will be generally followed. According to them, the analysis of the traffic noise impacts involves a number of steps:

- identification of activities and sites affected by noise from the highway;
- prediction of traffic noise levels;
- determination of existing noise levels;
- determination of traffic noise impacts;
- evaluation of abatement measures for reducing or eliminating the impacts.

Appendix VII discusses in detail how the assessment of noise impact will be done in ORIGAMI. The determination of units affected will be done using the GIS component, as explained before. The estimation of the noise impact will be done based on the general idea that there are certain acceptable limits for noise and that payment is justified to reduce noise above these levels. Reference values for the average monetary willingness to pay are discussed on appendix III. Payment willingness for special units (churches, hospitals, etc.) is expected to be higher. To determine this value the procedure proposed by the author uses a standard majoring factors defined by the user. ORIGAMI could however also be set up to extrapolate the cost based on the number of people benefited.

10.6 THE MRI EXPENDITURE OBJECT AND ITS RELATIONS

When activated, the *MRI Expenditure* will receive as an argument the *Status* object containing information about the basic data objects that should be taken into consideration during the analysis. By searching *Status* it can determine what is the current *Project* object (if there is none it can prompt Status to request a Project from the User). Having defined the Project to be analysed, the *MRI Expenditure* object activates the objects used to represent each of the parcels of the agency expenditure discussed in chapter 9, as seen in figure 10.6.

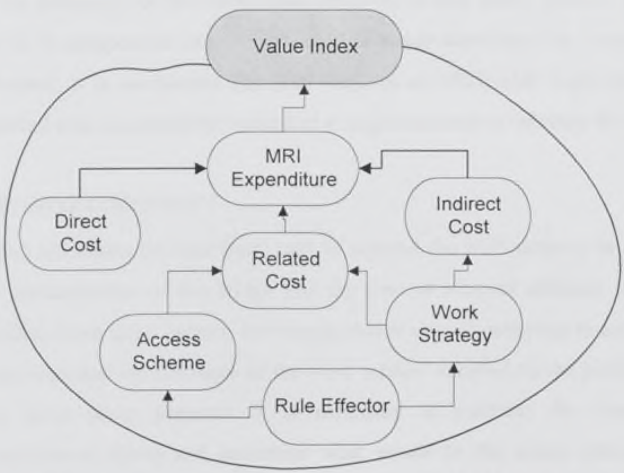

Figure 10.6 - Representation of the relations of the MRI Expenditure object.

The *MRI expenditure* object then direct the objects to calculate their values and combine the results obtained in order to produce a single expenditure figure to be sent back to the calling object, which ordinarily is the *Value Index* object. The most sophisticated calculations are performed by the related cost object, which relies on the *Rule Effector* object to process the fuzzy rules that are used to select the probable access scheme and work method. This information is necessary to calculate certain elements of the related and indirect costs.

DIRECT COST OBJECT

This object has the function of determining the basic cost of undertaking the MRI activity. In this initial version of ORIGAMI a very simple approach will be used to achieve this objective. As suggested in equation 10.8, the unit cost for the kind of activity implied by the strategy being considered (stored in the *Activity* object) will be multiplied by the amount of work to be executed (contained in the *Defect* object). The current *Defect* and *Activity* objects can be extracted from the *Project* object contained in the *Status* object.

$$DC(ProjID) = \text{Unit Cost}(ActID, StrategyID) * Q(Defect) \qquad \text{(Eq 10.8)}$$

Despite the simplicity of the calculations involved in this initial version, *Direct Cost* was kept as an independent object so it could be easily substituted for a more complex one if desired. It is envisioned that later versions of ORIGAMI might prefer to use more detailed cost compositions instead of a single unit cost to calculate this factor.

RELATED COST OBJECT

This object calculates the additional cost to support the MRI activity in view of the specific characteristics of the bridge and the type of element affected. It takes into consideration three main factors: the transportation cost of materials to and from site; the access costs and the influence of the work method adopted on the productivity. To calculate these three elements it is necessary to estimate the distance from supply/destination places and determine what would be the access scheme and the work method that would probably be chosen. If not available in the databases, the distances can be extracted from the GIS component using spatial analysis. Meanwhile, special objects were created to provide an estimate about the probable choice of work method and access equipment based on the use of fuzzy rules. These are described ahead.

ACCESS SCHEME OBJECT

The *Access Scheme* object has the function of defining the adequacy of each of the access equipment available to perform the MRI operation under consideration. The author decided that the standard version of this object would make use of the soft reasoning capability introduced in advanced systems to make an estimate of this adequacy. Fuzzy rules are used to compare the characteristics of the activity and the physical characteristics of the bridge with the capabilities and characteristics of the equipment stored in the database.

The selection of the access scheme will be a combination of various factors. To determine the factors that should be codified into rules the author relied upon a special exercise conducted with the experts. In this exercise, described in Appendix I, the experts were presented with a sample of 15 bridges and asked to reason aloud about what would be the access equipment that they would employ and what were the reasons behind this decision. From the data recorded it was concluded that the choice of equipment is determined mainly by the consideration of four factors: the height adequacy, the operational cost of the access scheme, the technical adequacy of the access scheme and the possibility of congestion. The operational cost can be taken directly from the database.

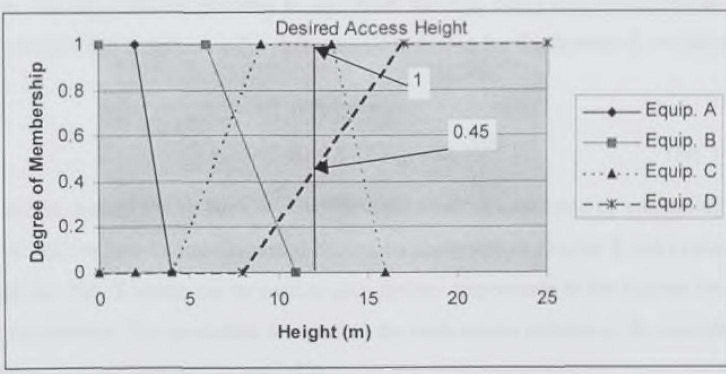

Figure 10.7 – Representation of the results of a height check using fuzzy comparison.

The height adequacy meanwhile will be determined by means of a fuzzy comparison. An internal method verifies the suitability of the equipment to work at a certain height by cross-checking the desired operational height against a set of fuzzy numbers that represent the range of adequacy of each equipment, as seen in figure 10.7. The membership functions of these fuzzy numbers correspond to translation of the capabilities of the access equipment/scheme into the universe of discourse 0-100 m, with 1 meaning optimal operation and 0 total unsuitability.

The other two factors to consider (Technical Adequacy and Congestion Impact) are more difficult to determine. They are therefore estimated in ORIGAMI using approximate reasoning. The *Access Scheme* object calculates these factors by activating a method that loads all the rules relating to their respective domains of interest and loads them one by one into *Rule* objects. It then activates an object denominated *Rule Effector* to process each rule. The *Rule Effector* takes into consideration the current conditions in terms of equipment, policy, etc. and delivers as a result a fuzzy conclusion and a firing strength. After all the rules of a certain domain have been processed the results are aggregated. As discussed in chapter 8, an appropriateness index is calculated by combining he fuzzy results using a fuzzy aggregation operation. Each rule has also an associated degree of confidence or belief strength (BS) that is demanded from the user when the rule is introduced in the database. This indicates how much that rule is considered important for the reasoning. The standard value for this parameter is 1 (meaning full belief). The method proposed dictates that the result of each rule R(j) will be elevated to the belief strength BS(j) and multiplied by the firing power FP(j) to calculate the aggregated conclusion for the domain d, as indicated below.

$$AC(d) = \Sigma\, [\, FP(j) \cdot R(j)^{BS(j)}\,] \qquad \text{(Eq. 10.9)}$$

After all the domains have been verified the final result is calculated by combining the result for of the four factors discussed before, as illustrated in chapter 8 and explained in appendix VII. Weights can be used to give distinct importance to the various factors being considered. The procedure is repeated for each access scheme to be considered based on the access equipment available.

The initial set of rules established to codify the knowledge is presented in appendix VI. While small, it was nonetheless adequate to represent the problem, as will be demonstrated in chapter 11.

Rule Effector Object

The *Rule Effector* receives and processes rules, transmitting back the results. The first step is to define the type of the rule: crisp or rule. Fuzzy Rules are handled by the main internal procedure. This checks the antecedent clauses and loads them as fuzzy numbers. It is then necessary to determine the current value for the parameters composing the rule. If this is not imposed by the user or given by the calling object, the *Rule Effector* will ask the rule object to check the value using the localizer function discussed in chapter 8. The procedure then advances to compare the actual value of the parameters with the reference values stored as part of the rule, determining the firing power. If the adherence is not complete and the firing power is between 0 and 1, a reasoning mechanism is activated to extend the conclusion to the current situation. The user can determine which inference mechanism to use. The result is then calculated and passed back, alongside the firing power, to the calling object. A flag in the rule object is turned on to indicate that the rule was processed. If the Rule object contains a crisp rule an alternative procedure is activated. This procedure attributes a firing power of 0 if the conditions of the rule are not satisfied and 1 in the other case. The results are sent back to the calling procedure.

Work Strategy Object

The *Work Strategy* object has a similar function to the *Access Scheme* object. It determines the appropriateness of adopting a certain work Method. The idea is to estimate what would be the probable work strategy that would be adopted in practice. This information is used to increase cost estimates in the case of difficult work conditions and to check the environmental consequences of the work. To identify the reasoning behind the choice of work method the author presented the experts with a series of situations and inquired about the possible strategy that they would adopt. Observing their behaviour it was possible to conclude that the following factors are usually considered: the characteristics of the bridge, the cost of the work method and the effect on users and the environment, especially the consequences in terms of congestion. Rules were created to encapsulate these considerations and are described in appendix VI. Six basic work strategies will be considered: Nocturnal, Full Closure, Lane Closure, Off Peak, Enclosure and Shuttle service. According to a review made by the author this list represent the majority of common strategies adopted. The user can however include more methods if desired. The methods must be described in terms of their characteristics. Linguistic variables will be used to express things like their noise impact, continuity, etc. In some cases it might be more interesting to store these parameters as numerical values and transform them using generic membership functions when necessary. This would apply to things like the set-up cost, for example.

Indirect Cost Object

The indirect Cost object calculates the additional cost that would be incurred due to factors not directly related with the MRI activity being performed. The indirect cost elements that will be covered in the initial version of ORIGAMI include the cost of setting-up the work site, the cost of environmental protection, the cost of traffic management and the cost of services removal and replacement. According to the experts all these are major items that can affect the cost. The proposed way of calculating each of these costs will be by using standard values derived from previous experiences. It is just necessary to characterise the bridge and the characteristics that could influence the costs. The GIS component for example will be used to check the position of the structures and determine if environmental protection is necessary. The traffic management measures will be considered as proportional to the ADT. It is envisioned that in the future the use of CBR technology could increase the capabilities of ORIGAMI. Appendix VII describes this object in more detail.

10.7 The Variation in Replacement Cost Object and its Relations

When the analysis arrives at this point, the cost of replacement will already have been calculated. It is just necessary therefore to establish the variation in the lifetime expectancy because of the adoption of a certain MRI alternative. The only other object activated by this object is the *Service Life*, discussed below.

SERVICE LIFE OBJECT

The estimation of service life could be done in the majority of the cases by multiplying the vector of probable conditions at the end of the planning horizon by the standard expected lifetime for an element in each of the condition states, as follows:

$$LF = LF(x, cs_i) * P(x, cs_i, T_p) \qquad \text{(Eq. 10.10)}$$

Where $LF(cs_i)$ is the expected lifetime for an element x in state i and P is possibility of the element x being in state i at the end of the planning interval.

There is a problem however when element are protected, such as painted steel beams. PONTIS just considers this as a different element that would have a more suave deterioration curve. But this is not very representative, because in fact the element will not deteriorate significantly until the protection fails. After this, if the protection is not repaired, the underlying element will start to deteriorate (changing condition states) and eventually will fail. There is therefore a sequence of deterioration curves with a certain unknown amount of overlapping. A precise solution for this problem is very difficult but at least some improvements on the way the problem is dealt with can be tried. The lifetime expected could for example be defined as the sum of the lifetime expectancy of the protection plus the expectancy of the unprotected beam:

$$LF = LF_{prot} + LF_{beam} \qquad \text{(Eq. 10.11)}$$

The amount of unprotected beam would be initially equal to zero and therefore no deterioration would occur. With the passing of time and the increase in the chance of failure of the paint the amount of the beam that would become unprotected each year would increase by the following amount:

$$\Delta Q(\text{Unprotected Beam}) = \Delta P\text{fail}(\text{protection}) * Q_0(\text{beam}) \qquad \text{(Eq. 10.12)}$$

The percentage of the element that would became unprotected in the current period is added to the amount already unprotected and from that point onwards the normal deterioration curve using the transition probabilities for the unprotected beam would be applicable to this portion of the element.

Table 10.2 shows three consecutive years in the lifetime of a particular protected beam to illustrate the concept.

Table 10.2 – Example of the Deterioration of protected Elements

Title	TP	Year n	Year (n +1)	Variation	Year (n +2)	Variation
Prot (cs1)	.01	5%	4.95%	-0.05	4.9%	-0.05
Prot(cs2)	.05	5%	4.80%	-.25 + .05	4.61%	-.24 + .05
Prot(cs3)	.08	70%	64.65%	- 5.6 +.25	59.72%	- 5.17 +.24
Prot (cs4)	.10	20%	23.6%	-2 +5.6	26.41%	-2.36 +5.17
Prot(cs5)	-	0%	2%	2	4.36%	2.36
Beam (P)	-	100%	98%	-2	95.64%	-2.36
Beam (1)	.06	0%	2%	+2	4.3%	+2.36-0.06
Beam (2)	.03	0%	0%	0	0.06%	+0.06
Beam (3)	.01	0%	0%	0	0%	0

10.8 The Opportunity Cost Object

This is a simple and self-contained object that will not in principle have to create any other object. It will just need to know the expected expenditure of the current single or combo project. In possession of this information it uses standard (or user defined) return and discount rates to calculate the current value of the opportunity cost or gain.

10.9 Summary of the Chapter

This chapter introduced the ORIGAMI system and proposed an object model for its appraisal sub-system based on the appraisal model discussed in chapter 9. The general format and function of each of the nineteen objects suggested to compose the initial version of the model were briefly discussed. It was shown how the new architecture would be used to support some of them, such as the determination of noise impact using spatial analysis or the selection of access scheme using approximate reasoning. The structure describe is intended as a guideline for the construction of advanced systems and a prototype built based on it will help in the verification and validation of the research, discussed in chapter11.

Verification and Validation

11.1 Introduction

This chapter contains the verification and validation of the proposals for change investigated along this thesis. The chapter initiates with a review of what constitute a verification and validation process and, having established this theoretical basis, proceeds with the definition of a strategy for testing of the concepts developed in this thesis. The strategy chosen by the author divides the verification and validation exercises in three blocks: concept, architecture and appraisal model, with emphasis given to the last one. The purpose of the first block of tests is to determine whether the ORIGAMI concept is fundamentally workable. The opinion of IT experts about the fulfilment of the design principles established in chapter 7 was elicited and a prototype was constructed. The second block verifies and validates if the various elements of the architecture are capable of working as envisioned and validates some of the results obtained. The third block does the same to the appraisal model proposed in chapter 9. The exercises seek to establish whether the information generated by the enhanced appraisal model can provide a suitable basis for the selection of MRI strategies and evaluate the difference of the novel approach in relation to more traditional methods.

11.2 Defining the Scope of Validation and Verification

The concepts of verification and validation are often confused or used interchangeably but they in fact address two distinct problems, summarised by Boehm [1979] as:

- Verification: "Are we building the product right?"
- Validation: "Are we building the right product?"

As indicated by this definition, verification is the process of experimenting with a previously developed model, process or tool in order to check if the behaviour obtained is cogent and the operation is robust in terms of output and processing. It is however necessary to stress that the use of simulations rarely yields completely reliable results because of the assumed simplifications [Merna, 1989]. Holloway [1997] argues that validity can be seen as the scientific equivalent of the everyday notion of truth and defines validation as the process of checking if the proposed modifications or improvements measure what they were supposed to measure and calculate what they were supposed to calculate. Validating a research therefore involves examining if the research findings reflect the purpose of the study and represent reality.

The combination of verification and validation seeks to establish the fitness for purpose of a product or methodology. Verification is an important part of validation since it is necessary to ensure that a process or tool operates correctly before analysing if it produces the expected results. Lewis et al [1979] remark nonetheless that a verified model or process can still produce meaningless results if it is not validated. Testing is the predominant technique used for verification and validation [Sommerville, 1992], and involves exposing the object being analysed to a variety of real or simulated situations and observe its behaviour. The existence of defects or inadequacies can then be inferred from any operation or output anomalies [Yusuf, 1998]. This is of particular importance with models, which are essentially abstractions of reality that incorporate simplifications and assumptions [Pidd, 1989]. It is necessary to check if they are efficient and adequate, giving the shortcomings of modelling, especially in uncertain situations. It is important to highlight that in all but the most simplistic cases testing can never be exhaustive [Hetzel, 1988]. The time constraints on the testing period, coupled with the infinite number of possible tests, limits the tester to executing a representative sample, that provides a satisfactory level of confidence. Given these constraints, the strategy for verification and validation adopted by the author in this thesis is discussed below.

11.2.1 Verification and Validation Strategy

It was considered necessary to evaluate the soundness of the various developments proposed in this work by performing some verification and validation tests. The author believes that it is vital to analyse if the general concept of advanced systems is sound and if the changes proposed are feasible in principle. It is also essential to define if the appraisal model has the potential to be an adequate management tool to support decision-making in Bridge Management and if its initial implementation can be done successfully. Tests will be performed to check this various aspects. More emphasis will be given to the issues related to validation, since the idea is to provide a framework for change and not effectively develop a fully working system. Considering these facts, the strategy adopted for the verification and validation process consisted of four phases:

- Verification of the viability of the ORIGAMI concept;
- Verification and validation of the main elements of the innovative system architecture proposed for advanced systems by the author (object orientation; use of fuzzy reasoning and incorporation of a GIS component for spatial analysis and interfacing with the user);
- Verification and validation of the novel appraisal model proposed by the author

11.3 Phase 1: Verification of the ORIGAMI Concept

The verification of the ORIGAMI concept was undertaken in two steps. First the ideas that form the basis of the concept were presented to a new group of experts specialised in information systems to check their opinions about how well they could be used to produce systems that would fulfil the behaviour expectancies discussed in chapter 7. After this, the author investigated if a prototype could effectively be built and if it would stand to the premises about flexibility, organisation and easiness for upgrading.

11.3.1 Opinion from Experts

A new group of experts was invited to participate in the evaluation of the ORIGAMI concept. This group was composed by an IT consultant from a large international consulting organisation, a Lecturer in IT in construction in a University and a Researcher in Intelligent Systems with experience in virtual environments and approximate reasoning using CBR. The experts were presented with a description of traditional Third-Generation Systems and familiarise with the concept of ORIGAMI. They were briefly explained the working of the systems by the author and asked to express their opinion about the potentiality of both architectures to fulfil the design criteria discussed in chapter 7. Additionally, they were asked to consider a third option consisting of traditional Third Generation systems with an added WINDOWS© interface, such as the version 3.0 of PONTIS©. The results are presented in table 11.1.

Table 11.1 – Expert evaluation of the potential performance of different systems.

	EXPERT A							EXPERT B							EXPERT C						
	F	O	A	T	P	I	Ov.	F	O	A	T	P	I	Ov.	F	O	A	T	P	I	Ov.
TG	4	2	5	1	5	3	3	6	6	7	3	6	5	6	3	3	4	2	5	5	4
TGW	5	6	5	4	6	6	6	7	6	7	5	7	8	7	6	5	7	5	5	8	6
ABMS	8	8	7	6	7	8	7	9	8	8	7	7	8	8	9	7	9	6	9	8	9

Where TG = Third Generation Systems, TGW = Third Generation Systems with Windows Interface, ABMS = Advanced Bridge Management Systems, F = flexibility, O = Openness, A = adaptability, T = transparency, P = progressiveness, I = interactivity, X = overall impression.

As indicated in the table, all experts considered the ORIGAMI architecture as more appropriate than the traditional architecture to achieve the results established in chapter 7. This indicates that the concept of ORIGAMI can be considered as superior given the objectives established for the evolution of BMS. It also encapsulates, according to the feedback from the users, the potential for creating a more modern and user-friendly tool.

11.3.2 Practical Evaluation: Development of a Prototype

To test the object model proposed and therefore verify, to a reasonable degree, the feasibility of the architecture advocated for advanced systems in this thesis it was considered necessary to explore how a prototype of the appraisal sub-system of ORIGAMI would perform technically. The building of a prototype is considered useful because it shows up gaps in the theory and forces the clarification of some of the concepts involved [Harris-Jones et al., 1992]. It is important to highlight, however, that as discussed in chapter 1 just high-level development was carried out, focusing on the relationships between objects and in the working of abstract model, without actually trying to create a fully operational tool with a workable user interface.

The conception of the prototype involved various steps: the choice of an OO programming language for the basic development of the objects; the definition of a scheme for data storage; the selection of a GIS development tool to implement the GIS component and, finally, the consideration of the use of a Shell for rule storage and manipulation. The programming language chosen was *Visual Basic V5.0*™ from Microsoft because this has a reliable and flexible development shell that allows the creation of graphical interfaces without the problems of memory management associated with the more powerful *C++* languages. The only drawback was the precarious support of inheritance but this was not considered as an unsurpassable problem and in the balance the author decided that this was the best option.

The GIS development software chosen was MapInfo. This is one of the most well known software used for desktop mapping and has a long tradition in the area of GIS applications [MapInfo, 1995a; 1995b]. It has already been used successfully by She [1997] to develop a spatial interface for a bridge information database. In relation to data storage, the author opted to adopt *Microsoft Access*™ as the basis for the construction of the databases. This choice was justified by the fact that this is the dominant relational database on the market and could be considered almost a *de facto* standard on the area. Finally, it was decided that no specific shell would be adopted for the rules. This was a reflection of the fact that a specific rule structure that is flexible and expandable is being advocated that would not fit perfectly into a traditional shell. This approach also reduces the complexity of the system and makes it more portable, because there is no need to include the libraries of the shell with the executable files if a compiled version of ORIGAMI is produced.

Having chosen the platforms for the development of the objects, it was necessary to test if the assumptions about the flexibility and soundness of a prototype built with them would be verified. The connection between objects using the Status object was successful. In relation to upgrades, the objects were also tested and they worked well. The routine for the selection of bridges from the GIS component was successful. No problems with memory were encountered. Since no effort was made to develop querying, reporting or data inputting facilities, the verification of the capacity to handle incorrect data input was not considered as necessary. The objects nonetheless coped well with missing data and the system architecture proposed has shown itself very flexible. After registering the objects in the main system registry they could be activated from any part of the prototype or even from other programs that comply with the active X protocol [McKelvy et al., 1997].

11.3.3 Summary of Findings relating to the ORIGAMI Concept

- The examination of the opinion of experts suggested that the concept of ABMSs is sound and that the structure proposed for ORIGAMI is superior to the one in existing systems in fulfilling the behavioural guidelines discussed in chapter 7.
- It was demonstrated that the ORIGAMI architecture could be implement in practice and that it is possible to develop further the object structure discussed in chapter 10.
- The choice of Microsoft Access as the tool to create the databases gives users the opportunity of managing data independently of the BMS software, an interesting capability if a distributed structure is adopted.

11.4 Phase 2: Testing of the Proposed System Architecture

Having shown that the ORIGAMI concept was considered sound by experts and that it was technically feasible to create a tool using the novel architecture proposed, the next step was to verify and validate the innovative elements of this architecture and determine if they can in fact contribute to the improvement of advanced systems.

11.4.1 The Concept of Object Orientation

The concept of objects was tested by developing some of the modules discussed in chapter 10 and testing their performance and easiness of access while verifying the efficiency of communications between them. Additionally, the capabilities for upgrading and modifying objects were examined. One of the findings was that the communication between the Main Interface and the GIS component could originate some problems. One of the solutions would be to use the specifically designed version of the basic language that accompanies the GIS software (MAPBASIC) to create the main interface. This would mean that the original control of the system would be in the hands of the GIS component. This would allow more flexibility in terms of the operation with the digital maps. When necessary the other objects would be created by this program. This option was tested and was successful.

11.4.2 Test of Geo-referencing and Spatial Analysis

The verification and validation of the GIS component encompassed three topics: a) investigation of the feasibility to create a digital representation of the network to be used in advanced systems; b) demonstration that digital maps could be used to identify and select bridges for analysis / display results and c) the examination of the viability of using spatial analysis functions to support certain parts of the analysis.

- *Verification of the viability of creating digital maps for use in advanced systems*

To use the GIS component capabilities it is first necessary to geo-reference the data. This implies the need for establishing a digital representation of the bridge network. The alternatives for creating reasonable representations were therefore examined. The easiest way to develop a digital representation of the network would be by customising digital maps already available. The GIS development tool chosen, *MapInfo*, comes with some samples of digital maps of the UK, containing counties boundaries, cities, A roads and Motorways. There is also considerable data available from the Ordnance Survey and other entities dedicated to support digital mapping. The author concluded therefore that, apart the fact that these resources can be very expensive, there is enough available data for creating the initial graphical framework in this way if desired.

Having the support digital map, the basic data about the network can be geocoded to it. The author tested this function in the software adopted with good results. Bridges can easily be introduced as points in a map if latitude and longitude data is stored in the database. The introduction of more detailed information at a higher resolution level is however required for certain analysis suggested for advanced systems. It might for example be necessary to divide the roads into links to allow certain functions to be performed, as discussed in Appendix VII. The problem is that for the spatial analysis it is necessary to have a better representation of the bridge than just a point. If more detailed representations are necessary it will normally be necessary to digitalise them.

Most GIS software support the input of data trough a digitalisation tablet. They will also use CAD files if a suitable geo-reference can be established. A simpler but less precise way to create digital maps is trough the adaptation of the contents of a raster image. Raster images are usually used as background but when properly geo-coded can be used as a basis for the creation of objects to represent the network links, the bridge and the surrounding houses, for example. The author has done this successfully for a small section of the city of Manchester in the UK. Figure 11.1 shows the combination of a raster image with a digital map of the main roads in the region of Manchester.

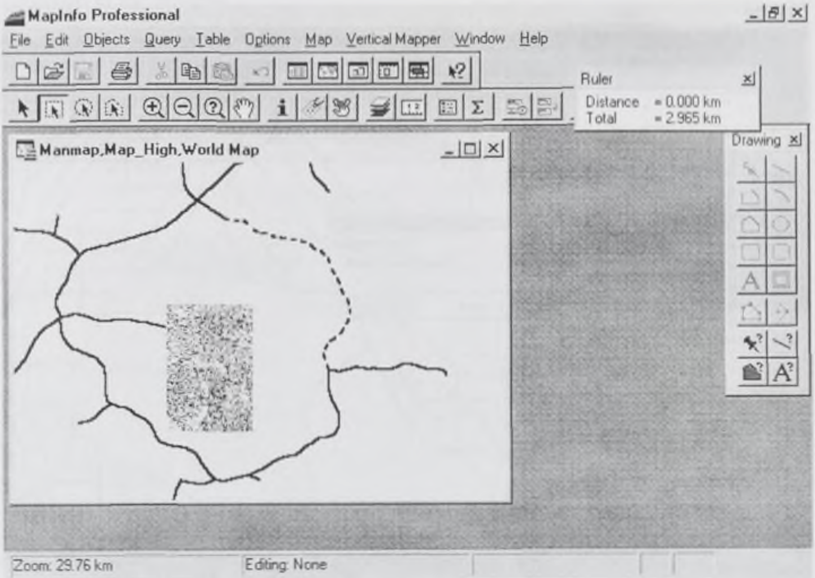

Figure 11.1 – Combination of raster image and digital map.

The projection system used to produce this integrated digital map was the OSR-80 system established by the Ordnance Survey. The use of this expedient provides a suitable background for the digitalisation of the bridge network and to locate the additional information necessary while at the same time improving the user interface. This can therefore be a low cost way to obtain a digital map. However, data that is more precise is usually available to bridge authorities and should be used if possible.

It is important also to highlight that authorities should use a single system of co-ordinates to facilitate the integration of existing digital maps with the information on bridge databases and customised raster images.

- Displaying of Bridge Data

Displaying of data in the GIS is an easy and natural task, as shown in figure 11.2. Some facilities of MapInfo even allow the creation of thematic maps to show the condition of the bridges.

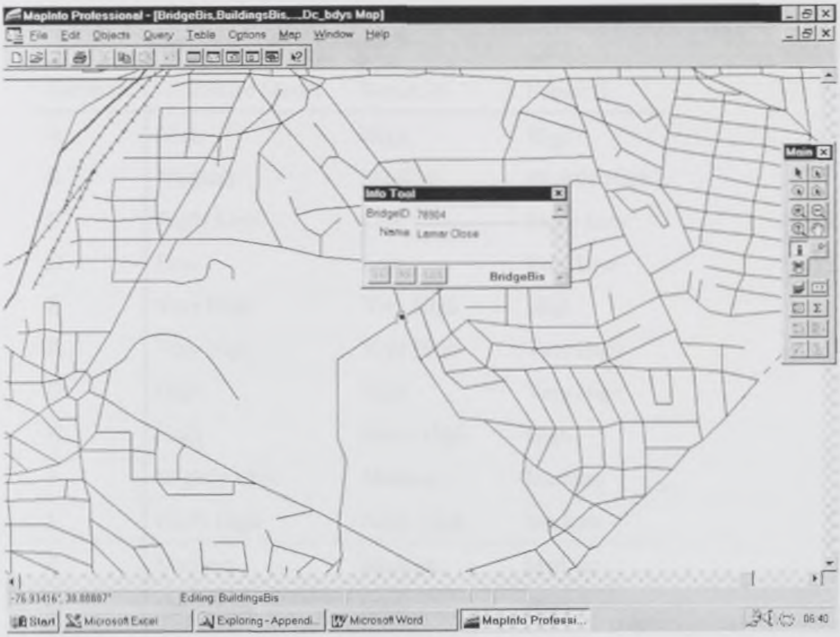

Figure 11.2 – Display of bridges using the GIS component.

- Use of spatial functions

Another useful characteristic of the GIS component is that it introduces the capability of performing spatial analyses. The main use for this capability in this initial version of ORIGAMI is to determine the noise impact. The GIS software allows the use of a *buffer* function that establishes an area around a certain object. The type of each edification located inside the interest area is then checked and their distance to the bridge measured using another spatial analysis function. The results are put in a text file. The *Noise* object then uses the noise sensibility model described in Appendix VII to calculate the noise sensibility of the area or the noise valuation model to calculate the monetary impact of changes in noise emission on the bridge.

To verify if the results obtained using these procedures are sound, an exercise was carried out. The noise sensibility of a set of bridges was estimate using the GIS capabilities and the aggregation model proposed by the author and the results compared to the opinions of experts. The results are shown in table 11.2.

Table 11.2 – Verification of the noise sensibility results calculated with the help of the GIS component.

Location	GIS/Noise Model	Expert A	Expert B
A	High	High	High
B	Medium	Medium	Slightly High
C	Fairly Low	Low	Fairly Low
D	Low	Low	Very Low
E	Very High	Very High	High
F	Very High	Very High	Very High
G	High	High	Very High
H	High	Fairly High	High
I	Slightly High	Medium	Medium
J	Fairly High	Fairly High	Medium
P	Medium	Medium	Medium
Q	Very High	High	High
R	High	Fairly High	Medium

The table contains the data for 13 locations and compares it with the opinions of two engineers that were asked to estimate what would be the probable impact on those locations. The first ten locations were a selection of traffic intersections or river crossings in the city of Manchester (the same ones used as part of the reasoning exercises with the main group of experts). The other three are new locations used to check the model in different conditions.

As indicated in the table, the results of the GIS model are in general agreement with the experts. The noise model in ORIGAMI seems to value the impact of noise slightly stronger than the experts, especially in the new bridges. However, since the difference was small, the current model is considered as being representative and the procedure of using GIS to estimate the noise is considered as verified as useful.

Beyond noise impact assessment, the GIS could also carry out other analysis to identify certain parameters about the bridge, such as if the structure is part of an emergency route or is located in a special environmental protection area. This means that much data that is currently stored in the bridge database could be easily determined during processing, saving storage space. This structure would allow a more dynamic and reliable management of the bridge data, since changes in the character of an area or route could be done directly in the GIS and all bridges affected would automatically register the difference next time they checked the data, reducing the chances of errors occurring because of lapses in updating fields.

11.4.3 Testing of Fuzzy Reasoning Procedures

In the initial version of ORIGAMI discussed in this thesis, fuzzy reasoning is mainly used to support activities in two domains: access method selection and work method selection. Special objects were created to handle the procedure in each domain as discussed in chapter 10. Both rely upon the *Rule Effector* object, which processes the rules. The verification of the fuzzy reasoning structure was therefore done by checking if the results produced by the *Rule Effector* are reasonable and by analysing their sensibility to changes in the system of values considered. The validation of the reasoning processes was done by comparing the choices from the *Work Strategy* and the *Access Method* objects with the choices that would have been done by experts in the same situation, as follows.

- *<u>Verification of the Adequacy of the Results Produced by the Rule Effector object</u>*

The initial step was to verify the accuracy of the fuzzy reasoning methods used in the *Rule Effector* object. As discussed in chapter 8, the author tested various inference mechanisms and a similarity procedure using just the "firing strength" was preferred. The first column of table 11.3 shows the different conclusions that would be obtained from a generic rule "if A if high then B is low" if an initial condition A* was assumed. As can be seen in the second column of the table, there is a lack of sensitivity for values greater than the initial argument A proposed in the rule, as discussed in chapter 8. If however more rules were established for more points on the universe of discourse and their results combined as described in chapter 8, the result can be refined. This is the case for example in the rules for noise adequacy described in Appendix VI.

Table 11.3 – Verification of the efficacy of the standard reasoning procedure used in the Rule Effector object.

Input Value (A*)	Result (1 rule)	Result (3 rules)	
		Individual	Aggregated
	(results shown as Fuzzy Result/Firing Power)		
Extremely Low (el)	H/0	H/0 + L/1+ M/0.05	Low (0.254)
Very Low (vl)	H/0	H/0 + L/1+ M/0.2	Low (0.287)
Low (l)	H/0.05	H/0.05 + L/1+ M/0.6	Fairly Low (0.354)
Fairly Low (fl)	H/0.1	H/0.1 + L/0.95+ M/0.65	Fairly Low (0.371)
Slightly Low (sl)	H/0.1	H/0.1 + L/0.6+ M/0.8	Slightly Low (.417)
Medium (m)	H/0.5	H/0.5 + L/0.6+ M/1	Medium (.482)
Slightly High (sh)	H/0.6	H/0.6 + L/0.1+ M/0.8	Slightly High (.586)
Fairly High (fh)	H/0.85	H/0.85 + L/0.1+ M/0.5	Slightly High (.636)
High (h)	H/1	H/1 + L/0.05+ M/0.5	Slightly High (.666)
Very High (vh)	H/1	H/1 + L/0+ M/0.2	Fairly High (.740)
Extremely High (eh)	H/1	H/1 + L/0+ M/0.05	High (.804)

The third column of table 11.1 shows the results that would be obtained if the additional rules below were adopted:

If A is low then B is high.

If A is medium then B is medium

The last column of the table shows the fuzzy outcome of the aggregation of the results of the three rules. These outcomes were obtained by interpreting the values in brackets, which are the result of the defuzzification of the fuzzy number obtained by the weighted sum of the fuzzy results of each rule. The final results obtained indicate that the answers are generally sensible and that even when the general fuzzy classification is the same there are differences in the numerical values that could be used to express the distinction in the consequences of the input conditions. The numerical results will be used to interpret the results of fuzzy inferences.

- *Verification of the Sensitivity of the Domain Aggregation Technique*

As discussed in chapter 8, this thesis proposes that rules inside each domain are added as discussed above but that the results of each rule domain should be aggregated using a weighted product instead of a weighted sum operation. The author decided therefore to verify the sensitivity of the aggregation technique used (which produces the appropriateness index for the selection of work strategies or access schemes). To this end, a sensitivity analysis using the work strategy selection procedure was carried out. As discussed before, the appropriateness of a work strategy was modelled in this thesis as a result of the multiplication of factors that express the technical adequacy, the noise adequacy, the congestion adequacy and the cost adequacy. Each factor is elevated to a weight factor that represents the importance given to that part of the selection criterion. Assuming that in a particular case three of the adequacy factors remain as medium (represented numerically by 0.517), figure 11.3 shows the effects of varying the other factor (let's assume it is the cost adequacy) from extremely low to extremely high. The figure shows the curves for various cases, beginning with a case where the importance given to the varying factor is just ¼ of the others to where it is 5 times greater. As observed in the figure, the model behaves sensibly in the whole range, with the effect of changes in the cost adequacy growing in relation to the relative importance of the factor to the sum of the importance of the others. The graph is limited by an horizontal line passing by the aggregated importance of 0.517, which represents the input condition where no importance is given to cost adequacy, and by a diagonal line, which would indicate that no importance was given to the other factors.

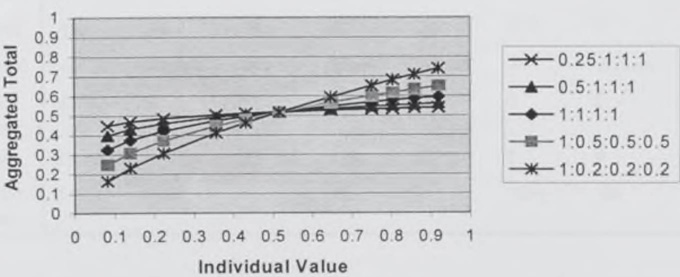

Figure 11.3 - Verification of the consistency of the rule aggregation mechanism.

- *Verification of Fuzzy Selection Procedures*

Having verified that the fuzzy inference procedures are basically sound and shown that the results obtained make sense, it was considered necessary also to validate the applicability of the results. A small number of rules derived from the interviews with experts were introduced in the rule database (and are described in Appendix VI). A simulation involving 8 hypothetical bridges and 6 work methods was undertaken. Pictures of the bridges were presented to the experts and their location pinpointed on the map. The experts were then asked to give their opinion about which work method would be more appropriate and give their reasons for it. The results of the choice made by the each of the main group of experts and the ones indicated by the system are presented in table 11.4. Details about the calculations performed are given in Appendix VIII. In the table, each symbol marks the choice of a group of experts while the numbers indicate the appropriateness of the work method according to the *Work Strategy* object prototype (which can vary from 0 to 1). The following system of weights was considered:

→ Environmental Adequacy Importance: Medium (numerical support = 0.516)
→ Cost Adequacy Importance: High (numerical support = 0.804)
→ Functional Adequacy Importance: Fairly High (support = 0.751)
→ Technical Adequacy Importance: High (support = 0.804)

Table 11.4 – Validation of the work method selection procedure using soft reasoning.

Work Method	Bridge							
	1	2	3	4	5	6	7	8
Closure	.47	.34	.28	.20	.42	.42	0.37	.20
Off Peak	.48>	.39 >	.49 >	.41	.35	.47>	0	.39
Nocturnal	.46	.58>>	.48 >	.50>>	.45>>>	.47	.47>>>	.50>>
Lane Closure	.47>>	0	.61>	.49	.22	0	0	.47>
Shuttle	0	0	.37	.42>	0	0	0	0
Direction Closure	0	0.35	.44	.30	0	.52>>	.46	.33

As seen in the table, the majority of choices is concentrated on the nocturnal and off peak strategies, which minimised the intervention impacts. The fuzzy reasoning procedure was capable to produce results very similar to the experts, with the best choice always being one of the choices of the experts and the subsequent choices usually covering the other choices made by them. The procedure is therefore considered as adequate to estimate the possible work strategy that would be chosen in a certain situation. A similar procedure was use to validate the procedure for selecting a particular access scheme to undertake a specific activity that would require access for underneath a particular bridge. The results are presented in Appendix VIII.

11.4.4 Summary of Findings related to the System Architecture

- The tests indicated that the use of modularization and the concept of objected orientation can be implemented in practice, allowing the introduction of flexibility in the architecture of ORIGAMI and providing a smoother integration between different systems, since modules can be accessed easily to provide an specific response.
- The use of fuzzy reasoning improves the communication between user and computer and facilitates the gathering of information. It is much easier to use linguistic variables to communicate with experts and register their expertise. The model used provided good response and can be extended to be more useful
- It was concluded that it is possible without greater problems to establish a digital representation of the bridge network to allow the undertaking of spatial analysis
- The introduction of a GIS interface allowed an extended and more natural evaluation of some of the external costs of maintenance. The introduction of these environmental costs contributes to a more representative CBA (Value Analysis), in line with emerging society perceptions.
- The combination of GIS and fuzzy reasoning allows ABMSs to demonstrate a higher degree of "intelligence". Geo-referencing allow systems to process spatial data simulating a "vision sense" (nonetheless limited to two dimensions unless 3D models or Virtual Reality is introduced, as discussed in chapter 8) while fuzzy reasoning allows them to extract information from the spatial data. Some effort however is necessary to create a suitable digital representation of the network and to codify the common-sense rules to develop this capacity.

11.5 Phase 3: Verification of the Appraisal Model

In this phase, tests were performed to verify the performance of the appraisal model as a tool for strategy selection and prioritisation. In the first part of this verification test complete calculations for a specific bridge were carried out to show the difference between the improved appraisal model and traditional benefit-cost ratios. In a second exercise, some sensitivity analyses were performed to assess the influence of variations in certain elements of the model. These special situations were considered to determine their consequences in terms of changes in the Value Index.

11.5.1 Impact on the selection of MRI Strategies

To perform this initial verification of the appraisal model the author decided to examine what would be the differences between the novel model proposed and a traditional approach regarding the selection of a MRI strategy for treating a certain element in a particular bridge. A hypothetical bridge was created based on data from a real bridge to be used in the analysis. The basic characteristics of the structure were:

Asset Characteristics: Length: 189 ft (57.6 m) Width: 30 ft (9.14 m)

Functional Characteristics On: ADT= 20.000 / Rural Interurban / Single

Functional Characteristics Under: River

Constituent Elements:

- 12 – Concrete Deck Bare – 5670 square feet
- 104 – Pre-stressed Concrete Closed Web-Box Girder – 378 linear feet
- 205 –Reinforced Concrete Column – 1 unit
- 215 – Reinforced Concrete Abutment – 2 linear feet
- 302 – Compression Joint Seal – 60 linear feet
- 321 – Reinforced Concrete Approach Slab – 2 units
- 331 – Bridge railing – 458 linear feet

Note: In an advanced system it would be expected that the elements were individually identified. Values such as the ones above would be calculated by aggregating the data of particular elements and would serve to perform certain general analyses.

The main problem of the bridge example was defined to be the deterioration of the unprotected concrete deck, which was assumed to be in Condition State 3 because of corrosion and spalling. For simplicity it was assumed that the whole deck was in the same condition and subjected to the same environmental conditions at time T_0 The remaining elements were assumed to be all in good condition (CS=1).

Three possible intervention strategies were defined as viable alternatives to treat the problems of this bridge. These are seen in table 11.5. It is useful to remember that, following the discussion in chapter 10, in an advanced system the user would be expected to have a great flexibility to choose and customise MRI strategies. This exercise will however be limited to consider the standard options that are found in-built in PONTIS. The basic characteristics of each of these MRI strategies are presented in the table. The unit cost values correspond to the ones used in the demonstration version 2.0 of PONTIS but were corrected to sterling pound and adjusted to the month of Nov/98.

Table 11.5 – Description of MRI strategies to consider.

Strategy Number	I	II	III
Description	Repair	Repair & Protect	Replace
Unit Cost (1998 prices)	£21.45	£38.06	£69.20
Probable Effect (TP)	0% chance CS=1	50% chance CS=1	95% chance CS=1
	100% chance CS=2	50% chance CS=2	5% chance CS=2

The results of the MRI strategy selection using the traditional analysis and the new appraisal model are presented below. Just the main outcomes of the calculations are presented here. Details about the values obtained are given in Appendix VIII.

- Calculation using a Traditional Appraisal Procedure

In traditional C/B analyses the cost of the intervention would be calculated by multiplying the amount of work to be done by the unitary cost of the MRI activity considered. The benefits meanwhile would mainly originate from the reduction of user costs in the case of improvement options and the difference in investment in maintenance and repair actions [Golabi et al., 1993]. The user cost moreover would be considered in a very simplified way, due to the lack of traffic assignment models, as discussed in chapter 10. The limited view of the impacts of MRI actions is one of the problems of the traditional approach, as discussed before. Another major drawback in the author's opinion is the fact that there is usually little or no indication about which kind of benefit was considered. Current systems do not make clear if the benefits of maintenance are related to the reduction of user costs or if they are a financial benefit deriving from the fact that correction now will prevent the need for action in the future. There is also no provision to allow the user to give different weights to these factors.

Table 11.6 shows the cost and the benefits for each strategy as they would be normally be calculated in existing systems. As seen in the table, the order of preference would be first strategy I, then strategy II and finally strategy III. No strategy however have a b/c ratio greater then 1, meaning that these investments would not be economically effective to undertake.

Table 11.6 – Summary of the results obtained using a traditional approach to appraisal.

Strategy Number	I	II	III
Cost	£121,621.50	£215,800.20	£ 392,364.00
Benefit	£94,139.39	£117.035,34	£137,593.09
Benefit/Cost Ratio	0.77	0.54	0.35

It is necessary to highlight that, in systems like PONTIS, the selection of an strategy to deal with a particular problem is not done in this way, but instead is a result of a cost minimisation exercise. The exercise would establish a steady state strategy that becomes the standard policy to deal with a certain element in a certain CS for all the bridges in the network. Chapter 6 discussed the problems created by such an approach, which are also emphasised by Vassie [1997]. This type of calculation is however employed in various systems for prioritisation and will be useful to illustrate the differences between the restricted view of cost ands benefits prevailing in existing systems and the broader and holistic view advocated by the author, as follows.

- Calculations using the Advanced Model

The author will now examine how the improved model proposed in chapter 9 would work for the same bridge. Equation 11.1 shows the format of the novel appraisal model proposed to evaluate a certain MRI strategy MSx:

$$VI\ (MSx) = (VBU + VRC - ECI - OCI)\ /\ MCI \qquad \text{(Eq. 11.1)}$$

Where: VI is the value index, VBU is the variation in bridge utility; ECI is the external cost of the intervention, OCI is the opportunity cost of the investment, MCI is the monetary cost of intervention and VRC is the variation in replacement cost.

To undertake the appraisal of the various competing MRI strategies according to the new model proposed by the author it will be necessary to recalculate costs and benefits considering the five elements seen in the equation, as discussed below

- <u>External Cost of Intervention</u>

The first element of the Value Index equation to be calculated is normally the external cost of intervention (ECI), as discussed in chapter 10. This ECI will be a direct consequence of the disturbance caused by the MRI action in terms of users and the environment. To assess it is necessary to determine the repercussion of adopting each of the possible wok strategies established by the user as a viable option. This demands the undertaking of a traffic assignment exercise for each of them, as follows.

Traffic Assignment: As discussed in chapter 10, the initial step of the analysis consists in the determination of the consequences of adopting different work strategies in the traffic flow. For this it is advocated that advanced systems should incorporate a traffic assignment model. Results for the bridge example were calculated based on a distribution of traffic flows determined using a traffic assignment model similar to the one used in the QUADRO software, as described in Appendix VIII. The hourly traffic distribution was calculated for an average day of the week and the consequences of limitations in speed and capacity imposed by the MRI intervention were then considered. Since the bridge carries a single carriageway road, the shuttle and lane closure strategies were considered as equivalent. Five work strategies were therefore examined: total closure (CLOSURE), direction closure (DIRECTION), direction closure with shuttle (SHUTTLE), direction closure with off peak shuttle (OFF PEAK) and direction closure with nocturnal shuttle (NOCTURNAL). Having determined the hourly distribution of vehicles and estimated the speed-flow relationships that each work strategy would generate in the work site, it is possible to estimate the number of vehicles detoured and determine the traffic impacts.

Traffic Impacts: The traffic impacts are the result of the reduction in average speed and the delays caused by the MRI intervention on the main route or the detour route. The average values obtained for time losses, number of extra kilometres travelled, increased cost of accidents and additional consumption of fuel for the bridge under analysis are shown in table 11.7. As seen in the table, all the work strategies cause some disruption in terms of time loss and extra consumption but the shuttle strategies are much less disruptive in general terms, because they reduced or avoid diversions. The values on the table were used to calculate monetary values for the external impacts, as follows.

Table 11.7 – Average impacts of each work strategy adopted (total number of vehicles affected = 26,667).

Strategy	Fuel Consumption (litres/veh)	Time Loss (min/veh)	Accidents (pence/veh)	Extra Km (per veh)
Total Closure	0.461	1.44	5.2	1.12
Direction Closure	0.220	0.70	2.6	0.55
Shuttle Lane Closure	0.038	0.44	0.45	0.05
Shuttle Off Peak	0.015	0.27	0.30	0
Shuttle Nocturnal	0.006	0.10	0.15	0

Valuation of the External Impacts: The external impacts express themselves in four basic ways, as discussed before: time losses, extra fuel consumption, additional vehicle operating costs and higher number of accidents. The individual values of the commodities involved - time, human lives, emission of pollutants and material damages during accidents - used in the calculations are given in Appendix VIII. They are a reflection of the values discussed in Appendix III and include:

- Societal Cost of the Loss of a Human Life: ~ £1,050,000
- Environmental Cost of fuel burning: ~ £0.57 /l (petrol) and ~ £ 0.45 /l (diesel)
- Average value of time per vehicle: ~ 0.10 pence /min

These values were used to calculate the various components of the ECI. A summary of the results is shown in table 11.8. The analysis of the results in the table shows that the environmental impacts are significant, being of the same order of magnitude of the VOC and representing between 17% and 30% of the total cost. This justifies the discussion about the need for considering these impacts carried out in chapter 4. A sensitivity analysis to check how changes in the values of the parameters used to calculate the various costs would influence the result is presented in section 11.5.2.

It can also be noticed in the table that the external costs vary significantly between work strategies. The use of a total closure strategy has, as expected, the greater impact, almost 15 times more than the use of a nocturnal work strategy.

Table 11.8 – External cost of intervention according to the work strategy adopted.

Work Strategy	User Costs Time	VOC	Acc.	Environmental Costs	Total Costs (per day)
Total Closure	£4120.03	£10165.78	£1382.13	£6757.70	£22,425.64
Direction Closure	£1991.35	£4877.41	£692.69	£3231.47	£10,792.92
Shuttle Lane Closure	£1253.40	£726.13	£120.51	£556.44	£2,656.48
Shuttle Off Peak	£761.03	£238.05	£82.59	£215.66	£1,297.33
Shuttle Nocturnal	£276.00	£99.44	£40.38	£99.09	£514.91

The option of diverting just half the traffic, using a shuttle service or a one-way restriction, reduces the cost by more than half. The shuttle seems to be more efficient because although the vehicles lose more time in crossing the bridge, it is necessary to divert fewer vehicles, avoiding the extra consumption and the higher VOC of an increased journey length. The results obtained should not however be analysed in isolation. Some of the most costly work strategies will in turn allow a better productivity, reducing the duration of the work and therefore affecting the agency expenditure (the Monetary Cost of Intervention, in the Value Index equation), with impacts on the Value Index. To make an accurate analysis of the situation it is necessary to consider all the results together.

- Selection of Work Strategy

After calculating the external impact of the MRI interventions the next step, as discussed in chapter 10, is to determine the cost of the intervention for the agency. One important consideration is that part of the related and indirect costs are fixed (lump sums) but another part varies with the amount and duration of work to be performed. To estimate the duration of the work it is necessary to check the productivity of the MRI activities being considered, as indicated in table 11.9.

Table 11.9 – Initial estimate of the duration for each MRI strategy.

Strategy Number	I	II	III
Productivity (estimate)	15 m^2/h	5 m^2/h	2.5 m^2/h
Estimated Duration (h)	35 h	104 h	210 h

To translate the duration in terms of days it is necessary to define the work strategy that would probably be adopted, because this will influence the number of work hours per day and consequently impact the duration. Having already calculated the impacts of each work strategy it is possible to use the fuzzy selection procedures discussed in chapter 8 to determine the most probable work method that would be adopted for each course of action. As discussed in chapter 10, this would be done by the *Work Strategy* object, which considers the various rules applicable to this domain, processes them and determines the most probable strategy that would be implemented. A summary of the calculations involved is shown in Appendix VIII. The results of the work strategy selection procedure are given in table 11.10.

Table 11.10- Selection of probable work method and its consequences.

Strategy Number	I	II	III
Work Method (probable)	OFF PEAK	OFF PEAK	SHUTTLE
Reduction in Productivity	15%	15%	5%
Number potential work hours/day	20 h	20 h	24 h
Effective work hours /day	20 h	20 h	24 h
Duration (days)	2 days	6 days	14 days

As seen in the table, the choice of work strategy resulted in the use of an Off Peak Shuttle service for MRI strategies I and II. Meanwhile, the adoption of a continuos Shuttle service was found as the best alternative for strategy III (replacement), which demands greater continuity. The use of an Off Peak shuttle service is defined as increasing the duration of the work by about 15%, due to the disruption cause by the interruption during peak hours. The use of a shuttle service is assumed to have a minor impact, just around 5%. These values were estimated by the experts and are considered adequate for the aims of the present study but the author suggests that in-depth studies should be carried out to validate or modify them and produce reliable values for other situations.

Having the work strategy and the modified productivity, the duration in days can be estimated. It depends on how many of the available hours provide by a certain strategy are effectively used for work. In this exercise, it was assumed that all possible hours would be used for the undertaking of the work, despite the need for higher payments for the workforce during night shifts (hypothetically the user could be allowed to customise the strategy to define another work regime or the BMS software could be directed to automatically explore different periods of work to find the most cost-effective). The duration of the work for each strategy considered, in the conditions established, would be equal to 2 days, 6 days and 14 days respectively.

- Selection of Access Scheme

Theoretically it would also be necessary to select an access scheme. However, since the activity occurs on top of the bridge and access is not considered a problem, no special access scheme is necessary.

- Determination of the Agency Expenditure

In the advanced appraisal model proposed by the author to the cost of execution must be added the cost of support (related cost) and the indirect costs. Chapter 9 discussed what elements would compose each of these costs.

The direct cost is calculated using just the unit cost. To calculate the related cost the following factors were considered: set-up costs, access scheme, haulage costs. As discussed before, more factors can be added if desired. The indirect cost will depend on the location of the bridges and its functional importance. The details about how to calculate each of them are given in Appendix VII. The results for the bridge under analysis are summarised in table 11.11.

As seen in the table, the situation was defined as not to alter the direct costs significantly. This situation was imposed by the author to facilitate the comparison with the traditional appraisal results. The only large increase corresponds to the extra expenditure due to the increased cost of labour for out-of-normal work hours (overnight). The related costs in this example have been reduced just to the set-up costs and contribute less than 1% to the total costs. In relation to the indirect costs, there will be no need to spend money in the removal and replacement of services because the bridge does not carry any and there will also not be necessary to provide any environmental protection.

Table 11.11 – Calculation of the agency expenditure according to the new appraisal model proposed.

Strategy Number	I	II	III
DIRECT COST	£121,621.50	215,800.20	£ 392,364
Haulage costs	-	-	Not significant
Set-up and Overhead Costs	£1,200	£3,645	£7,000
Access Scheme		Not Necessary	
Access Cost	£ 0.00	£ 0.00	£ 0.00
RELATED COST	£1,200	£3,645	£7,000
Environmental Sensitive		No need for protection	
Env. Protection Cost	-	-	-
Traffic Management	£2,240	£2,720	£7,211
Services Removal/ Inst.	-	-	-
WM Additional Cost	£10,945.93	£19,422.01	£39,236.40
INDIRECT COST	£13,185.93	£22,142.01	46,447.40
TOTAL AGENCY EXPENDITURE	£136,007.43	£241,587.21	£445,811.40

♦ Variation in Bridge Utility

To calculate this component it is necessary to determine the value at risk in the case of collapse and cost of inadequate performance. The first element will depend on the Bridge Value, the user cost at collapse and the risk of failure. These were calculated as follows:

Bridge Value: As discussed in chapter 9, the Bridge Value will be a combination of the asset value with the functional, historic and strategic value, creating a notional value for the bridge.

- Asset Value: The asset value was calculated by multiplying the amount of each element by its cost of replacement. The result for the bridge example was £4,356,816.00.

- Functional Value: The functional value was calculated by adding the external costs that would originate from the total closure of the bridge during each year over the whole planning interval. An annual traffic growth of 2.8% was considered, resulting in a gradual increase in the costs. The values obtained are discussed in Appendix VIII. The functional value for the first year was estimated at

£7,686,407.25. Due to the traffic growth, the functional value in the fifth year was estimated at £9,459,544.00.

- Historic Value: The historic value was calculated as nil because the historic relevance of the bridge was defined as being "low", that is, equivalent to a standard bridge.

- Strategic Value: The strategic value of the bridge was calculated using the model described in Appendix VII. For a strategic relevance assumed as high this represented a value of 30,803,874.69 for the bridge being analysed.

The notional Bridge Value at year 0 (present time) was therefore estimated as £42,847,097.44 and it grows to £44,620,234.54 at the fifth year. As can be seen, the notional Bridge Value is much higher than the asset value and becomes a more realistic representation of the "intrinsic value" that an expert would attributed to the structure if faced with the chance of losing it.

Risk of Failure: The risk of failure was determined using the procedures discussed in chapter 10. A risk function was established for each element to relate their condition states with a specific risk level. A series model was then assumed to calculate the risk for the whole bridge, with the relative importance of elements (extracted from the interviews with the experts) acting as weights for combining the individual risks, as described in Appendix VIII. The variation in risk for each of the intervention strategies in relation to the do-nothing strategy was then calculated for each year in the planning period. These values are presented in Appendix VIII.

User Cost at Collapse: The analysis of the peak flow indicated that, during the peak hour, an average of 4.72 cars would be simultaneously at the bridge. Considering the average value of an accident as £1,124,413, as detailed in Appendix VII, the user cost at collapse was estimated as £5,311,291.40.

External Costs of Deterioration (Disutility): The next step was to determine the cost of bad performance. This is represented by the external cost caused on the users and the environment by the compromise of the functionality of the bridge. Three possibilities were considered: the reduction of speed caused by the deterioration of the deck, the increase in the risk of accidents by the same motive and the imposition of weight restrictions that result in the diversion of heavy vehicles. Appendix VIII shows how these values were calculated. For example, it was established that when the dec: reached Condition State 4 there would be a 50% chance of very heavy vehicles being detoured. If it reached Condition State 5, all heavy vehicles would have to be detoured. The number of vehicles detoured was then used to modify the speed-flow relationships in the detour route. The increase in emissions, vehicle operating costs and accidents, as well as the time losses, where then estimated as it was done during the determination of the external costs of intervention. Care was taken however to consider specific characteristics, such as the fact that increase in emissions would be mostly of diesel fumes instead of petrol fumes. The time losses and operating costs for the vehicles detoured were also adjusted to represent heavy vehicles only.

Costs of Failure Correction: Depending on the strategy chosen, a certain proportion of the element being considered might reach, during the planning interval, a failed condition. This would prompt the authority to act to correct these problems in the short term. The model assumes however that strategies are defined in a way that, if the failed area were not greater than 1%, these corrections would be postponed to the end of the interval. Since the planning interval adopted is short, this usually prevents the need for interventions during the planning interval, which would go completely against the whole management philosophy adopted. The cost of failures is then calculated at the end of the interval and added to the disutility. Having at the end of the interval, at least in theory, undertaken the rehabilitation of the failed parts of the element, the remaining lifetime is calculated from the resulting distribution of condition states, as discussed in chapter 9.

Having collected all the above data, the variation in bridge utility (VBU) can then be estimated. Table 11.12 shows the results of the calculations for each of the MRI strategies considered. As seen in the table, the bridge utility does not vary significantly (just around 8%) between the three MRI strategies if a 5-year planning horizon is considered. This is because all the interventions restore the condition of the bridge in the short-term to a good state, where the performance is not compromised. They become therefore roughly equivalent in relation to changes in utility. The absolute amount of benefits nonetheless is significant, representing well more than the MCI of Strategy I and close to the total cost of Strategy II.

Table 11.12 – Evolution of the Variation in Bridge Utility for each MRI strategy.

	Reduction in the Value At Risk	Savings in replacement of failed elements	Reduction in the external cost of deterioration	VBU
Strategy I				
T_0	£2,118.63	£-	£7,732.31	£9,850.94
1st year	£6,238.56	£-	£13,822.73	£20,061.29
2nd year	£5,926.23	£-	£14,135.91	£20,062.13
3rd year	£25,119.79	£-	£18,809.73	£43,929.52
4th year	£23,877.36	£566.41	£19,614.91	£44,058.68
5th year	£64,175.95	£534.35	£23,044.91	£87,755.20
Total	£127,456.51	£1,100.76	£97,160.49	£225,717.76
Strategy II				
T_0	£2,142.27	£-	£7,732.31	£9,874.57
1st year	£6,398.93	£-	£14,360.31	£20,759.23
2nd year	£6,078.57	£-	£14,688.87	£20,767.43
3rd year	£25,639.89	£-	£20,282.11	£45,922.00
4th year	£24,371.74	£566.41	£21,157.38	£46,095.54
5th year	£66,174.08	£534.35	£25,804.82	£92,513.25
Total	£130,805.47	£1,100.76	£104,025.79	£235,932.03
Strategy III				
T_0	£2,166.99	£-	£7,732.31	£9,899.29
1st year	£6,543.26	£-	£14,844.12	£21,387.39
2nd year	£6,215.68	£-	£15,186.53	£21,402.20
3rd year	£26,107.97	£-	£21,603.97	£47,711.94
4th year	£24,816.68	£566.41	£22,506.20	£47,889.28
5th year	£67,972.40	£534.35	£28,181.03	£96,687.79
Total	£133,822.98	£1,100.76	£110,054.15	£244,977.90

- Variation in Replacement Cost

The new appraisal model establishes that it is necessary to consider the impact of each different course of action in terms of the future expenditure that will be incurred to replace the existing structure. The cost of replacement is defined as the Asset Value discounted over a period equal to the remaining lifetime expectancy.

Each of the MRI strategies considered extends the lifetime expectancy by a different amount and therefore affects the present value of the replacement cost, as shown in table 11.13.

Table 11.13- Effects of different MRI strategies in the lifetime expectancy and replacement cost.

Strategy Number	0 (do-nothing)	I (repair)	II (repair and protect)	III (replace)
Condition State Distribution (%)	0 / 0 / 85.74 / 12.95 / 1.25 / 0.04	0 / 63.61 / 34.43 / 1.90 / 0.06	32.93 / 46.39 / 19.65 / 1 / 0.03	62.56 / 30.90 / 6.3/ 0.18 /0
Remaining Lifetime (present time)	56.4 years	-	-	-
Remaining Lifetime (in 5 years)	52.35 years	114.38 years	132.38 years	148.59 years
Discounted replacement cost	£154,090.93	£4,151.80	£1454.02	£565.55
VRC	£8.808.01	£149,939.13	£152,636.91	£153,525.38
Savings in Future Maintenance	- £196,122.30	£193,659.04	£116,500,99	£137,058.74

The results obtained indicate that the VRC will play an important part in the definition of the Value Index, since it has a same order of magnitude as the costs and the variation in Bridge Utility. It is important to highlight that these results were based on the use of data about the remaining service life at each condition state obtained from PONTIS. The data was obtained from experts, it is subjective and has not been fully validated. The author considers that more studies to establish reliable values must be undertaken. Until then, these values could be used as an approximation.

The results on the table were determined assuming that if any amount of the deck elements reached Condition State 5 or failed it would not be replaced until the end of the interval, as discussed before. The cost of repairing failures was estimated at the end of the interval. This amount is not incorporated into the replacement cost because it is avoidable depending on the MRI strategy adopted. It however influences the remaining service life if performed. The user can choose to adjust the distribution of elements before the lifetime remaining is calculated. This was done in the current example. However, as discussed in chapter 9, the user can opt for including an additional factor to represent the saving in terms of avoided maintenance in the next period, similarly to how benefits would be estimated in existing systems such as PONTIS. The respective values are shown in the last line of the table. They are similar to the "benefits" considered in the traditional approach because the cost of failures is small for the planning horizon adopted.

- Opportunity Cost of Investment

The last factor to consider is the potential loss of earnings that would be made because the money was spent. Considering a social return rate of 6%, the OCI for each alternative would correspond to the values shown in table 11.14

Table 11.14 – Opportunity cost for each MRI strategy.

Strategy Number	I (repair)	II (repair and protect)	III (replace)
OCI	£34,374.77	£61,059.19	£112,675.19

- Value Index

Having calculated all the elements that compose the improved appraisal model, it is now possible to determine the value indexes for each of the MRI strategies, as shown in table 11.15.

Table 11.15 – Value Index for each MRI strategy.

Strategy Number	I (repair)	II (repair and protect)	III (replace)
VBU	£136,007.43	£241,587.21	£445,811.40
ECI	£225,717.76	£235,932.03	£ 244,977.90
VRC	£34,374.77	£61,059.19	£112,675.19
OCI	£2,594.68	£7,784.04	£37,190.72
MCI	£149,939.13	£152,636.91	£153,525.38
VI	2.49	1.32	0.56

The analysis of the results obtained using the new appraisal model indicates, similarly to what happen using the traditional model, to the strategy I as the preferred one. However, the ratio in this case is well above one, suggesting that it would be adequate to carry out the intervention. Strategy II has also a ratio greater than one with just Strategy III presenting a Value Index below one. This change occurs because the new model considers a broader range of benefits. One additional advantage is that the new model offers much more information about the distribution of the impacts, allowing the undertaking of what-if or other exploratory analysis if desired.

If the savings in maintenance expenditure in the next period were considered the ratio alter yet more towards being favourable to the benefits. The strategy to carry out to the prioritisation stage would therefore be the first one, which gives the best "value" for the money invested. Further tests are however carried out below to check how sensitive the model is to changes in the parameters used to calculate its components.

11.5.2 Sensitivity Analysis

The next series of verification and validation tests involving the appraisal model consisted in the verification of the consequences of variations in certain parameters.

- *Sensitivity of the Value Index to the importance given to the various elements of the appraisal model*

Figure 11.4 shows how the Value Index of the preferred option (MRI strategy I) would vary if the weight given to each of the four basic elements of the appraisal model was differentiated and reduced progressively towards zero. The figure shows how the use of weights can be used to give different importance to each of the model's components and at the same time indicates the relative magnitude of each component.

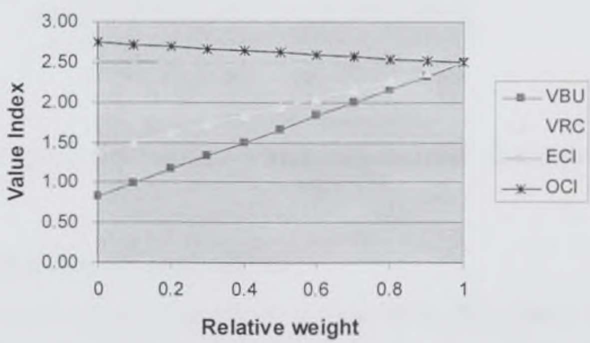

Figure 11.4 – Variations in VI due to changes in the importance of its components

The importance of the variation in utility is evident. The external costs meanwhile are the less important in this case. This could be expected since the off-peak shuttle service does not generates any great disruption of the traffic flow and the work is carried out quickly (just 2 days). If the duration of the intervention increased then this factor would become more important and reduce the utility.

- *Sensitivity of the Value Index to changes in the historic and strategic relevance attributed to the bridge*

Figure 11.5 shows the changes in the Value Index that would occur if the historic and the strategic relevance attributed to the bridge were altered. As seen in the figure, the strategic and historic relevance tend to impact the Value Index more if they are very high, This is seen as and indication that the model exhibits a sensible behaviour. The impact of changes in the relevance attributed to a bridge in the value index is significant, reaching up to 40%. This is considered as one important way to justify investments in the bridges that are most important to the good working of the network, as suggested by the government.

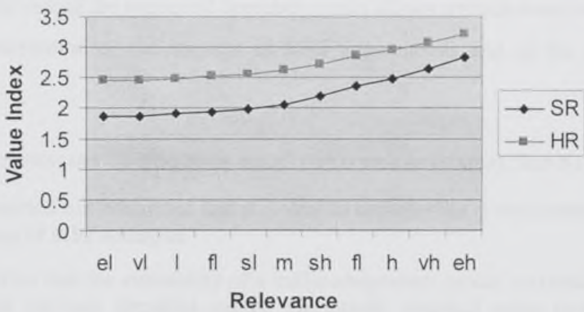

Figure 11.5 – Variation of the Value Index due to variations in the relevance attributed to the bridge

- *Sensitivity of the External Cost Component*

Figure 11.6 shows how the external cost of intervention (ECI) would vary for variations in the values attributed to the non-monetary impacts and in the length established for the worksite. Because the off peak option does not implies detours, the effect of changing the value associated with emissions and accidents is small. The increase in the value of time is much more important in this case, because many cars are suffering delays. The increase of the site length also similarly a very strong effect on the external cost, because it increases the congestion.

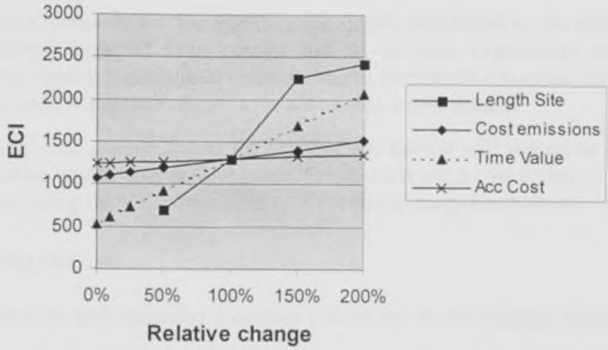

Figure 11.6 – Sensitivity analysis of various parameters that affect the ECI.

Many other analyses could be carried out but the ones above are considered sufficient to illustrate the sensitivity of the model and verify that it behaves sensibly. They also indicate that the use of the improved appraisal model allows a much more precise and thorough consideration of the impacts of MRI interventions and of the effects of deterioration.

11.5.3 Summary of Findings related to the Appraisal Sub-System

- The tests carried out confirmed that it is vital to consider the environmental cost in the appraisal of MRI strategies
- It was verified that the availability of a traffic assignment model is critical to allow the used of the new appraisal model. The results obtained using models from QUADRO (modified when necessary to suit the new appraisal model) were generally good.
- The results also indicate that, despite the inaccuracies in some of the models employed and the need of more research to improve them, the general concept encapsulated in the new appraisal model are sound. The model responded adequately to variations in the conditions of the bridge and has shown itself more sensitive to variations in the parameters involved than traditional methods.
- It was verified that, even for a relatively small bridge without many problems as the bridge example, the impact that are not considered in traditional systems would already be significant enough to subsidise a change in the decision about undertaking the preferred MRI strategy.
- It was verified that the amount of calculations needed to supply the information needs of the new model is greater than for traditional models. However, the author verified that it is possible to automate the majority of them, allowing the user to interact just to provide the information about the basic parameters and the system of values to be used.

- The tests indicated that the approximate models developed by the author based on knowledge ext-acted from experts and on previous experiences could provide sensible results. It is necessary nonetheless to start studies to refine these models to allow the new appraisal model to produce even better results.
- It has become evident during the analysis that there is still numerous opportunities for further improvements to be made. Emphasis is put by the author on the question of associating the GIS component with the traffic assignment model.

11.6 SUMMARY

The verification and validation exercises carried out in this chapter demonstrated that new appraisal model, supported by the innovative system architecture, provides ORIGAMI with a powerful tool for the selection and prioritisation of MRI strategies. The inclusive character of the model allows the consideration of a wide range of impacts and removes a great part of the subjectiveness that is usually associated with decision-making in bridge management. Further progress will be necessary to improve the models and define the most appropriate set of values that should be used to reduce the various effects to a monetary basis. The author nonetheless demonstrated that with the development of the model and the associated procedures a sound basis has been established for the creation of an Advanced System compatible with the framework for change advocated in chapter 7.

Chapter 12

Conclusions and Recommendations

12.1 Conclusions

The author set out in this thesis to achieve three aims: a) discuss the status quo and establish the need for evolution in terms of Bridge Management and Bridge Management Systems, b) propose a path for the creation of more advanced systems, and c) demonstrate the viability of introducing some of the most promising changes considered necessary to improve systems. Considering the development and the findings of the work, a series of conclusions have been drawn. These are discussed below relating to the objective initially pursued. It is important to highlight before the conclusions are discussed however the fact that they are valid given the constraints initially imposed to this work, as discussed in chapter 1. Many findings were the result of an analysis of the reality of Bridge Management in Brazil and the UK and should be understood in this context. Also, the validation and verification exercises, while successful, were designed to test just the viability of the concepts involved. Further analysis will have to be performed to define the best structure for an advanced system in practice. It will be necessary to develop the OO conceptual model proposed into a workable OO design to create a fully operational tool.

1. Review of Knowledge and Development of a Process View of BM

The first objective established for the thesis was to review the basic knowledge about Bridge Management, analyse its scope and identify the steps composing this process.

The author discovered that, notwithstanding the increasing importance given to the topic of Infrastructure Maintenance and the growing interest in the subject of Bridge Management, the knowledge in this domain is still not very well structured and does not have well established boundaries. Despite these limitations it was possible for the author to identify the main elements that should constitute the Bridge Management process.

The effort started with the examination of the scope of the process. It was observed that, despite the theoretical notion that BM should envelop the whole lifecycle of a bridge, in practice its effective scope is limited to the operation phase. Given this limitation and reviewing the references to the concept in the literature, the author concluded that the process could be seen as divided in four basic steps: diagnosis, prognosis, therapy selection and treatment. The author argued that it is necessary to understand very well how these steps are structured and interrelate if the management of Bridge Maintenance is to be carried out successfully. Using a well-known process modelling technique a process model for Bridge Management was therefore created and validated with experts.

The process model proposed provided an insight into the range of activities necessary to allow the rational management of the bridge infrastructure and constituted a firm reference for the other discussions carried out in the work. Each of the main activities composing the process was discussed and it was found that many advances have occurred in the last decade, such as the emergence of the concept of elements and the use of techniques to forecast deterioration using Markovian Decision Processes. The evidence collected however suggests that the amount of research still necessary is enormous, because of the complexity of the issues involved.

The conclusion reached is that it is possible to establish a process vision of BM despite the fragmentation of knowledge in this domain. It was also concluded that while all the stages of the process are important, the most significant part of the process in relation to this thesis is the Therapy Selection stage, where the majority of decision-making activities are carried out. The appraisal activity was identified as especially important in this context because it combines all the data previously processed and provides vital information for the selection and prioritisation of MRI strategies.

2. Examination of the Path of Evolution of Bridge Management Systems

The next objective was to investigate the origins and the path of evolution of Bridge Management Systems, examining how they are structured and discussing their role in Bridge Management. The literature review allowed the author to identify how Bridge Management Systems have emerged from Pavement Management Systems and have evolved in the last two or three decades. A survey of existing systems showed that the leadership in this field is undoubtedly with the U.S., especially since the imposition of legislative obligations for developing such tools. Important efforts have also been identified on Europe, with emphasis on the systems developed in Finland and Denmark.

The analysis of the evolution of systems led to the proposal for a typology for Bridge Management Systems, which was elaborated by tracing a parallel with the traditional classification of Information Systems. First Generation systems were defined as database management tools while the Second Generation consisted of systems whose main function was to combine inspection data using simple procedures, characterising data processing tools. The Third Generation was defined as including the current systems that have the capacity of using pre-defined routines to process data into information, therefore categorising Management Information Systems.

The innovative typology proposed by the author established a clear pattern for the evolution of BMS systems and for the first time linked it to the evolution of information systems in general. The analysis of the evolutionary trend contained in it served to illustrate the great development of these tools in the last two decades and allowed the author to explain how their role has progressively shifted from mere data recipients to decision-making assistants. The author deduced from this undertaking that the role of BMS in Bridge Management decision-making will continue to be enlarged in the future.

The next step was to examine the structure of systems and investigate where changes would probably occur. The author identified that the majority of existing systems are still relatively rudimentary in terms of user interface and system architecture. Given the growing capabilities of computers and the increasing information needs of Bridge Management, the author concluded that there is a tendency toward the emergence of a new generation of systems. The author reasoned that new systems will have to incorporate "intelligent" components to allow them to make inferences and extract more knowledge from the stored data, in this way enabling them to become more useful "assistants" during decision making. Changes are also necessary to improve the communication with the user and to create ways to deal with graphic and spatial data.

The conclusion is that there is a clear trend towards the development of improved systems and that these systems will be more open and sophisticated. The author concluded that a new generation of BMSs should emerge in the near future. The user interface and the contents of the analytical core were identified as the areas more prone to change but the author deduced that the whole system architecture will have to be overhauled. The consequence will become more flexible, user-oriented and open. The author additionally concluded that is vital to understand the main role of a BMS as a decision support assistant that makes use of technology to systematically analyse quantities of data that humans cannot deal with. They do not substitute but complement bridge engineers, extending their capabilities for dealing with numerous needs at the same time. To create systems capable of performing this role it is necessary to analyse how decisions regarding MRI strategies are taken, as follows.

3. Investigation of the Question of Decision-Making in Bridge Management

This objective involved understanding how decision-making is carried out in Bridge Management. The main focus was the identification of which decision criteria to adopt to select and prioritise MRI strategies. An important contribution was the development by the author of an outline of a soft diagram explaining the relationships between the various parties involved in the process of bridge use and management. The understanding of these relationships helped explain the evolution of the decision-making procedures used in Bridge Management Systems, justifying the gradual change of the focus from the structural consequences to the economic ones. It also explains why systems have more recently started to give more emphasis to the consideration of user costs. The soft representation of relationships however suggests that some factors are still not being considered in a structured manner, such as the external impacts of deterioration and the environmental impact of MRI interventions.

The author therefore deduced that current decision-making practice should be modified to allow the incorporation of these impacts in a structured decision framework. Given the fact that the main policy adopted for public investment today is Value for Money this led to the suggestion that decisions should be made based upon the notional "value" of a MRI strategy, with "value" being understood in a broad sense as encompassing all impacts of deterioration and interventions. Referring back to basic economic theory, the author reasoned that the best way to express value would be by using utility functions. The idea of adopting a bridge utility function was therefore investigated. This function would be the mathematical expression of how society values the various impacts of deterioration and maintenance.

The conclusion extracted from these discussions is that decision-making in BM should evolve to consider, beyond safety, the cost to users and society. The inclusion of environmental measures is considered as especially necessary in view of the growing sensibility of society about the topic. The author also concluded that to allow this a more flexible and holistic decision-making structure, capable of expressing the contradictory and dynamic requirements of all members of society, is necessary.

4. Discussion of the Role of Economic Appraisal in Decision-Making

The fourth objective was to establish whether economic appraisal could be used to support decision-making in Bridge Management and, if proven, to define how this should be done. A discussion about the different dimensions of the concept of value demonstrated that it is necessary to reduce all impacts to a single basis and that cost is the most adequate reference. A review of various economic analysis techniques gave evidence to the fact that the choice of technique is ultimately a reflection of the aims of decision-making. Considering the demands of decision-making in Bridge Management, the technique considered most appropriate was the incremental benefit-cost ratios. Having defined cost as the common basis for analysis, it becomes necessary to translate all MRI impact into a monetary basis for comparing them. This led to the examination by the author of various valuation mechanisms for estimating the value of non-monetary impacts. It was demonstrated how techniques such as Willingness-To-Pay and Stated Preference could be utilised to produce monetary values for non-monetary commodities such as time and atmospheric emissions.

The significant aspect of this conclusion is that Economic Appraisal should be the basis for decision-making in Bridge Management. The author showed that cost is a natural expression of value and demonstrated that, despite the limitations in the valuation techniques for non-monetary goods, it is possible to reduce the majority of impacts involved in Bridge Management to a monetary basis. It is therefore argued that this should be the basic dimension to which all impacts should be reduced. The author additionally showed that the best metric to use during economic appraisal exercises would be to compare investment alternatives using an incremental benefit-cost ratio.

5. Justification of the need for further development of BMSs

The next objective involved the demonstration of the need for advances in the domain of Bridge Management. The collection of opinions from experts demonstrated that they have mixed feelings about the usefulness of BMSs but indicated that in general they expected more from these tools. It also indicated that they consider existing systems to be too rigid and restrictive. The analysis of the feedback from implemented systems showed that users are generally not satisfied and demand advances in terms of the behaviour and capabilities of the systems. Meanwhile the examination of the limitations of current practice undertaken by the author gave rise to doubts about the efficiency of certain procedures for costing and appraisal of MRI strategies. The author found that existing systems do not fully satisfy users' requirements and that there is a strong need for improvement. The next step was to analyse if there are opportunities for advances and the author demonstrated that there is currently a combination of technical advances and changes in society's aspirations that creates a real momentum for change in this domain.

The conclusion therefore is that the critical analysis of the status quo carried out by the author was successful in exposing the limitations of existing systems and demonstrating beyond doubt that there is a need for improvement, while providing evidence to the fact that there is support for the undertaking of these changes.

6. Identification of Desirable Characteristics of an Advanced System

The next objective was to characterise what would compose an advanced system. This was based on the analysis of the possibilities of progress discussed in the literature, the opinion of experts from Brazil and the UK and the understanding of the nature of the problem of Bridge Management gained during the development of earlier parts of the work.

The initial step towards defining what should constitute an advanced system was the elaboration by the author of a set of design guidelines, later validated by experts, that summarised how these tools are generally expected to behave. The next step involved the investigation of a innovative architecture for advanced systems, based on the incorporation of recent IT developments. The author made a conscious effort to tie together some research topics that have matured in recent years and have already been used extensively in other areas, like the use of GIS and object-oriented technology. The deduction was that it is necessary to provide a more open structure for advanced systems. It is also considered necessary to introduce some "intelligence" in these tools to improve the way decision-making is carried out by simulating the capacity of human beings of making sense of complex and uncertain situations. The creation of multi-reasoning intelligent hybrids combining traditional programming techniques and fuzzy logic was selected to this end. The final step was the consideration of improvements in the internal procedures used in the analytical core of Bridge Management Systems. Three areas were identified as promising in terms of potential for improvement: condition analysis, condition forecast and appraisal.

Having established a general framework describing what would characterise an advanced system, the author proceeded to select which parts of it should be developed in this research. The selection of changes to implement was made by the author based on the analysis of potential benefits achievable as registered in the literature and indicated by the elicitation of the opinion of experts. The chosen options included on the technical side the incorporation of object-orientation, geo-referencing and soft reasoning and, in relation to the procedural changes, the development of an improved appraisal model.

The conclusion reached was that a new generation of systems could be developed and that certain IT techniques would have a major role to play in the creation of these systems. The author also concluded that the most promising element of an advanced system to develop would be the appraisal sub-system. This element could make use of the innovative system architecture being proposed to support an improved appraisal model that would allow systems to improve their decision-making procedures and produce a more accurate way of selecting and prioritising MRI strategies. The next two objectives are involved with the refinement of this element.

7. Development of an Innovative Architecture for Advanced Systems

This objective involved the investigation of how to use certain IT techniques for establishing an improved architecture for advanced systems, which would significantly differentiate them from their predecessors. Three possibilities were examined: object-orientation, soft reasoning using fuzzy logic and geo-referencing using a GIS component. The use of object orientation is a fundamental part of the new architecture. It allows modularization to be implemented and establish the basis to transform BMSs into virtual entities that can grow and reorganise themselves to fit the needs of the users. Two basic types of objects (data and procedural) were created by the author to fulfil the needs of independence and flexibility. An investigation of fuzzy inference models was performed to define how best to process and aggregate rules. It was decided that a fuzzy similarity method should be defined as standard and that the aggregation of results should be done used a product operation. Tests carried out demonstrated that the results obtained this way were consistent. The flexible structure for storage and processing of rules developed by the author means that the rule base of the system can grow in complexity over time. The introduction of a GIS component gave systems a graphical interface and the author demonstrated how geo-referencing bridges could help in analysing certain impacts such as noise.

The conclusion is that the combination of the technical advances proposed provide the basis for the development of an innovative system architecture that would have a better interface with the user and allow systems to evolve into intelligent assistants capable of reasoning in uncertain or imprecise situations. This would be the first time that Bridge Management Systems would incorporate such capabilities and this could open various new opportunities for the operation of these tools. The innovative architecture proposed by the author in this thesis is therefore a major contribution to the evolution of Bridge Management Systems. Its various elements provide a sound basis for the creation of improved systems and offer numerous possibilities for further development.

8. Development of a New Appraisal Method for Advanced Systems

This objective involved verifying the possibility of establishing a new and more comprehensive appraisal model that could improve decision-making in advanced systems. This is considered the most critical part of the work since the model takes into consideration the theoretical contributions and uses the capabilities offered by the new architecture to establish an improved approach to the selection of MRI strategies.

The author decided, based on an analysis of the relevant literature, that the model should be established based on an extended benefit/cost ratio. The author demonstrated that this would be a suitable format because it is naturally compatible with a VFM policy. The thesis innovates by proposing that the appraisal model should consider, beyond cost and benefits measured by the bridge utility function, the external impacts, the opportunity costs and the repercussion in the lifetime expectancy. The model produces as a result a value index (VI) that indicates what is the change in value obtained for each unit of cost invested in a certain strategy. This is used for selecting and prioritising MRI strategies.

To support the new appraisal model the author reasoned that it would be adequate to make two further advances: a) define a reasonable way to measure the benefits in terms of bridge utility; b) establish a more reliable way of determining the agency expenditure since in conventional systems there is a weak relationship between the costs and the specific characteristics of the bridge and the MRI activity. A new classification of the elements of agency expenditure was identified by the author as necessary for better costing and it was demonstrated that this classification should be composed of direct, related and indirect costs.

The conclusion to be derived is that it is possible to develop a more extensive and coherent appraisal model of MRI strategies for advanced systems and that the use of the Value Index is adequate for undertaking a holistic approach towards the consideration of bridge impacts. The author concluded that the use of the proposed model would add flexibility and transparency to the decision-making process, allow the consideration of a large number of effects and establish a firm social basis for the consideration and comparison of investment options. This would lead to the definition of socially justifiable criteria for the establishment of MRI programmes.

9. Production of a Generic Model of an Advanced System

This objective involved the development of a generic example of an ABMS based on the various suggestions for improvement discussed in the thesis. The author created and developed conceptually the outline of an ABMS system denominated ORIGAMI.

Since the task of building the whole system would be unfeasible the author chose to progress into the elaboration of an object model just for the appraisal sub-system, which was defined previously as the main focus of this research.

The thesis contains an overview of the various objects proposed by the author for forming the appraisal sub-system and explains how to make use of the new architecture based on object orientation, GIS and fuzzy logic to add new capabilities to ORIGAMI. The resulting model exemplifies how the appraisal sub-system could be computationally implemented. Connections with established systems were discussed, since the data needs of the system are significant. Additional research will be required to define the most adequate format of the models for the precise assessment of certain impacts. However, the author demonstrated that the innovative appraisal model could be implemented making use of the innovative architecture to provide a tool for better decision-making in advanced systems. The author also concluded that the flexible nature of the object-based architecture proposed and the use of approximate reasoning provide an adequate basis for the incremental construction of advanced systems because they can produce less precise but still useful results in the absence of the necessary data. While a full system using the ORIGAMI concept is not developed the appraisal sub-system is envisioned as a stand-alone tool that could connect to and use information from other existing systems but would have the capacity to manipulate the resulting information in order to enhance the results.

The conclusion is that the application of the concept of advanced systems is feasible. The author demonstrated that the innovative architecture and the novel appraisal model are viable and can be fit together in a suitable way for the creation of the most critical element for decision-making in an advanced system, the appraisal sub-system. Additionally, the author concluded that the use of a bridge utility function would have two important consequences: a) make explicit (and therefore open for discussion) the system of values used to reach decisions about the prioritisation of bridgeworks; b) allow and stimulate the consideration of a wider range of impacts, especially the environmental ones that are increasingly relevant in public decision-making.

10. Test and Validation

The final objective was to perform some verification and validation tests. The author tested the theoretical viability of the concept of advanced systems by subjecting it to the evaluation of IT experts. The results indicated that experts believe that an advanced system such as the ORIGAMI system proposed in this thesis would have a greater adherence to the design criteria than existing systems. A prototype containing certain elements of the object model suggested for the appraisal sub-system of ORIGAMI was also developed to show the practical viability of producing such a tool. Both the opinion of the experts and the development of the prototype demonstrated that the concept of advanced Bridge Management Systems is feasible.

The next step was to verify the novel architecture advocated in the thesis for advanced systems. The tests performed indicated that the architecture is sound. The approximate reasoning procedure was demonstrated in principle to be effective. However, the rule base used was very small and it would be advisable to extend it significantly to improve its robustness and coverage. The rule structure adopted was specifically designed to facilitate the input of additional rules. The GIS have shown themselves to be a promising tool but the question of data collection and modelling to support it is a serious one that need to be addressed. It is also still necessary to effectively cross-reference all the network representations of transportation data to a unique map, as discussed by Sutton [1996].

The author also verified the various elements of the Appraisal model to demonstrate that, despite the simplifications adopted, the introduction of the changes proposed would be able to reproduce the natural reasoning of an expert and provide a more accurate estimate of cost and benefits. The final tests were designed to assess how advanced systems would perform in practical terms. A simulated set of bridges was used to verify how the new appraisal model would differ from traditional practice. This was aimed at verifying if the extended appraisal model was significant and if the new classification of costs could have significant implications to the prioritisation of MRI activities. The results indicated that the use of the new appraisal model is sound and that it can effectively affect the prioritisation of activities.

The main conclusion presented from the analysis of these various results is that, despite the provisory and simplified character of some of the models used and the lack of precise data for feeding the new appraisal model proposed, the novel procedures introduced by the author effectively gave a more adequate representation of the system of values that should be considered in defining MRI strategies. The author believes that, while further developments will be necessary, this certainly justifies the continuation of the research in this area.

Summary of Achievements

The author considers that the work has been generally successful in the fulfilment of the aims. Important theoretical contributions were made with the consolidation of the existing knowledge in the form of a proposal for a process model for Bridge Management and a typology for Bridge Management Systems. The introduction of the concept of advanced systems is an important achievement of the thesis. The author has shown that an increasingly computer intensive and distributed management structure is expected to evolve and that it will be necessary to produce more open systems. A framework for the development of a new generation of improved systems was proposed. These systems will have to be user-friendlier, flexible and dynamic to attend user expectancies and offer support for decision-makers to rationally manage the network of infrastructure elements. The author investigated how to respond to this need by developing an innovative system architecture and an enhanced appraisal model for use on an Advanced Bridge Management System (ABMS).

12.2 Additional Conclusions

The author considers that it is adequate to make some considerations about additional conclusions that emerged during the development of the thesis, as follows.

- **Pure network analysis should be avoided in BMS**

Another conclusion is that the use of a pure network approach as in PONTIS 2.0 can be misleading because of the consideration that a certain MRI strategy will have the same cost in different bridges is not sound. As demonstrated in the body of the thesis, the cost of intervention is closely linked to the characteristics of the bridge, as are many of the benefits. The author advocates therefore that a mixed approach must be taken, with a project-level analysis to determine the most probable strategy to each bridge considering its particular characteristics, followed by a network level prioritisation procedure. In this way it could be defined what would be the most appropriate course of action considering the real specific characteristics of the bridge. Since this is indicated by the value index, no other alternative would bring better value for money.

It is simple them to compare the indexes for the whole network and, subjected to budget restriction, define the set of bridges (or the portfolio of MRI actions) that would bring the biggest increase in value for the available resources.

- **Relationship Condition State and Risk**

The assessment of the appropriateness of a certain MRI strategy is largely based on the verification of the consequences of letting a certain bridge stay in a certain Condition State versus the benefits brought by maintenance or improvement. The problem is that currently there is a dissociation between the CS and the degree of risk that the bridge is being exposed to (structurally and functionally speaking) The conclusion is that to have a reliable way determine these consequences it is necessary to explore the relationships between risk and Condition State. This was identified as a major research area, that is already receiving attention but that will need even more attention in coming years.

- **Extension of the value index model to other infrastructure elements**

An additional conclusion is that, while not precise, the use of a social view of impacts, the reduction of all these impacts to monetary values and the use of a economic appraisal technique based on the concept of value can lead to a decision-making procedure that could be extended to other infrastructure elements. If the same system of values were used consistently, comparable results would be produced that could be used for analysing different public investment options. This would allow the objective consideration of competing investment strategies not just between individual bridges but also in relation to other alternatives for public expenditure.

- **Bridge Authorities Need to Prepare for the Implementation of a BMS**

Other important conclusion is that Bridge Management Systems should not be used as black boxes. Bridge authorities must take their time to understand how the systems work. They should also spend time collecting data relevant to their structures because some models are fairly sensitive to the data used. It is interesting to highlight that bridge agencies in Brazil and the UK are currently interested in the implementation comprehensive systems for Bridge Management. It is fortunate to observe that, although clearly stating the desire to operate systems in line with the most recent developments overseas, in both countries the authorities have shown a preoccupation with respecting their own particular characteristics when producing these systems. The author support this stance and is confident that the framework for the development of advanced systems presented in this work can provide a suitable basis for these authorities to develop open systems customised to their own needs and capabilities. Given the flexibility shown in the ORIGAMI model, these could even include existing systems where their replacement is not consider adequate or timely.

Authorities should also consider the implication of the system in correlation with the whole existing system for bridge management. It is not uncommon for the operation of a sophisticated Bridge Management System to be hampered by legislation or political requirements that restrain the proper functioning of the system. The maintenance strategy is normally based on technical criteria, such as the optimisation of bridge conditions over the whole network and the minimisation of costs. The priority of the various maintenance needs would be normally the result of some kind of cost-benefit analysis, since Value for Money is the prevailing policy, as discussed in chapter 3. However, the authorities in charge of maintenance could, however, in view of legal requirements, be requested to adopt an alternative "worst first" policy, which usually would not be the best solution. It is therefore important and, in some cases, to update related pieces of legislation in order to allow the management systems to give the most useful results.

12.3 Recommendations for Further work

The innovative character of exploratory types of research means that the number of questions answered tends to be smaller than the number of new questions raised. This was the case also in this thesis. Many issues discussed will have to be examined in greater depth in subsequent research efforts. Science is progressive, cumulative and co-operative and it was the desire and the hope of the author that this thesis could be an additional piece in this jigsaw of knowledge. Some suggestions for further studies that could build upon this work and proceed in its trail of improving Bridge Management Systems are given below.

- **Implement the Appraisal Sub-System in practice**

The first suggestion would involve the continuation of the development of the appraisal sub-system proposed. There are various opportunities for improvement, including developing the input and reporting facilities and determining how better to integrate the GIS and the traditional interface. Valuation methods for noise assessment and pollution will also have to be reviewed. Finally, it would be necessary to extend the validation effort for larger samples of data.

- **Investigate further modifications to the architecture of advanced systems**

One interesting option for further advances in the opinion of the author would be the introduction of case based reasoning as a screening process for the approximate reasoning. The hybridisation of the reasoning mechanism with the combination of fuzzy sets with neural networks also seems promising, as exemplified by Honavar and Uhr [1995]. The use of active monitoring sensors in new bridges will also demand adaptations in the traditional routines that compose a Bridge Management System.

- **Refine the Models used for Impact assessment**

An important sequence to the work done would be the investigation of how to improve the existing models and the study of how better to obtain the data for using them. Some of the models used to calculate the values for the appraisal model in this thesis have still to be validated in full while others are very rudimentary. More complex models for tasks such as traffic assignment and determination of noise dispersion could be envisioned. It is however essential to consider the data needs and establish the viability of using any new model in practice before they are considered for incorporation in ORIGAMI. Other question that needs to be investigated is related to the applicability of the simplified models proposed in the thesis. It is necessary to stress that the data utilised to subsidise some of the modelling efforts was specific to the cities of Manchester (UK) and Porto Alegre (BR). Consequently, any extension to other localities should be preceded by a critical review of their adequacy to other conditions.

- **Develop other elements of the ORIGAMI system**

The second group of proposals would involve the continuation of the development of the ORIGAMI system. This would include the creation of the remaining subsystems.

Special attention should be given to the development of work packaging tools to aggregate the results produced by the appraisal sub-system.

- **Promote the study of the external costs**

The need for considering the external costs in the appraisal was one of the focuses of this thesis. It is important to develop better relationships between interventions and deterioration and the environmental impact. Noise and atmospheric emissions are relatively easy to measure but other less objective effects such as visual intrusion should be investigated to see how they could be incorporated in the analysis. In relation to the user costs, their assessment during interventions has received a fair amount of attention from bridge authorities. The alleviation of user costs due to inadequacies has also been well structured. Nonetheless, it was verified that there is a lack of studies in the area of user cost generated by the deterioration of bridge elements. The author concluded that these costs should be considered if a comprehensive utility function is to be created. The results obtained in the thesis using approximate models to estimate them suggest that they can have a strong influence in certain cases. More studies are hence needed.

- **Study the Deterioration Forecast Procedures**

An important area for further studies would be the investigation of better procedures for deterioration forecast. The definition of transition probabilities is still subject to various doubts (see chapter 6). It is necessary to carry out studies to determine if they should vary depending on the time spent on a condition state, for example. It is also critical to establish a clearer relationship between condition states and risk. It would also be interesting to verify if the customisation of the TPs according to the specific characteristics of each bridge was feasible. Finally, it would be necessary to investigate the effects of interactions between elements' conditions in the transition probabilities.

- **Develop an intelligent inspection component for advanced systems**

Finally, a possible subject for further work would be the development of an improved component for supporting inspection using the capabilities introduced by the new architecture. The author believes that more intensive use of computers during inspections will occur in the future and that, instead of being used just as an electronic notepad to input data, systems could be use as an active source of information and knowledge. Provided with a multimedia capability and linked to the main database via cellular telephone, the computer could display background information concerning the bridge or the deterioration mechanisms involved. The instant access to libraries of cases, photographic registers of earlier inspections and general data about the previous history of the bridge would be an important capability that could help inspectors to develop a better understanding of the nature and importance of certain defects. GIS could provide bridge engineers with a clearer and more extensive picture of the problems faced while soft reasoning could play an important role in helping inspector to determine the bridge condition by acting as an expert assistant.

- **Study the integration of ABMSs with other Infrastructure Systems**

Another promising area would be the study of the possibility of integrating Bridge Management and other infrastructure systems. It is important to highlight that, while the thesis focused on the bridge infrastructure, the general principles discussed could be extended to other infrastructure elements given the adequate allowance for the existing operational differences. The work can be seen as a preliminary exercise in the development of integrated "intelligent" infrastructure management systems. This approach would make sense in terms of optimising the resources while providing an objective decision for budget distribution and policy–making. The potential for the development of the ORIGAMI model is considered as very encompassing and extensible to other infrastructure elements. The incorporation of a GIS element is seen as a natural stimulus toward this but there are various technical question that need to be investigated before a simultaneous and smooth management of different infrastructure elements can be implemented in practice. If consistently used, the appraisal model proposed in this thesis can act as a common basis for the comparison of investment alternatives provided that a common system of values is adopted.

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Appendix I

Summary of Knowledge Elicitation Results

- *Introduction*

As discussed in chapter 1, a series of interviews with experts on the field of Bridge Management was organised to allow the elicitation of expert knowledge to substantiate some of the discussions carried out in this thesis. The interviews were designed to elicit information that would allow the author to understand the expert's perceptions of the status quo in terms of Bridge Management and measure their expectations and desires about changes on the structure of Bridge Management Systems. They also allowed the gathering of data that helped build some of the models used in the prototype of the appraisal sub-system of ORIGAMI. Finally, the results were also used to validate some of the ideas and concepts proposed in the thesis.

- *Interview Design*

The author decided to undertake the knowledge acquisition trough interviews because this is considered to be the best method to gather detailed data and understand the expert's problem-solving processes [Meyer & Booker, 1991]. Questionnaires by mail or other remote data acquisition methods are not so effective because they do not allow the knowledge engineer to have close contact with the experts. A combination of methods was used during the interview. The initial part was composed of a questionnaire, since direct questions are the simplest way to elicit knowledge [Musen, 1989]. However, as argued by Johnson [1983], sometimes experts respond to questions with believable but inaccurate answers because much of the knowledge is tacit and therefore unavailable to consciousness. This induces the expert to respond in a way that the results of the question register what is called a reconstructed reasoning method, usually composed by procedures that are largely endorsed in the domain, but that do nor reflect the real practice. To register the authentic method of reasoning used by the experts in relation to MRI strategy selection, exercises conforming to the technique of protocol analysis were also posed to the experts. In both cases, questionnaires and reasoning exercises, visual aids were introduced whenever possible, since they are considered as an important tool to help guide the experts' reasoning process during the interview, as pointed out by Finkler and Kosecoff [1985] and Meyer and Booker [1991].

- *Elaboration of the Questions*

The first part of the interviews was composed of a questionnaire. This questionnaire was conducted in an interactive format. A graphical presentation using the PowerPoint software was produced to introduce the questions. This semi-structured approach was considered adequate because it allowed a greater interaction between the knowledge engineer and the experts. It also made easier for the author to clarify the meaning of the questions to avoid misunderstandings of scope. This was important since the problem under study has very wide boundaries and is fairly complex.

The phrasing of the questions was carefully examined to ensure that it did not present undesirable bias. While it is practically impossible to avoid some degree of bias [Payne, 1951], the questions should be drawn in a way that stimulate the production of a neutral tendency, with opposite biases balancing themselves. Finkle and Kosecoff [1985] call attention to the importance of avoiding terms that could cause confusion or mislead the interviewees. For this reason, a basic level of language with limited usage of technical terms was adopted. Nevertheless, Belson [1994] reports various experiments where a strong distortion of meaning was observed even using common terms. He calls for a very precise and short formulation of the question and for a close monitoring of the perceptions of the respondent. In view of these problems, the length of the questions was kept short, following recommendations of Meyer and Booker [1991]. This limitation is justified also by studies carried out by Payne [1951], which demonstrated that people's comprehension of written sentences tend to diminish after the threshold of 25 words. A neutral answer sheet was used to prevent bias.

A small number of questions were open-ended. In these cases there was no need to mark them in the answer sheet and discussion between the experts was encouraged, with a board being used to register the brainstorming results. This approach was adopted in the cases when it was considered that providing a list of alternatives could induce the experts to adopt a particular behaviour pattern, compromising their answers. It was the desire of the author to let the experts have flexibility to answer these questions. The format of the majority of questions has been however defined using a scale of linguistic terms ranging from extremely low to extremely high. These fuzzy questions allowed a direct comparison between the various expert opinions but retained enough flexibility to allow experts freedom of expression. Finally, a reduced number of questions was more structured. In these questions experts were asked to chose a value from a list of alternatives or provide an estimate of the value. This approach was used to produce more precise results that could be implemented in the development of the prototype. It was considered that the combination of open and fuzzy questions, supplemented by the occasional numeric question, would increase the chance of gathering a real picture of the perceptions and expectancies and was a better approach than the use of closed or language delimited questions. Another reason for adopting this strategy was the fact that some researches have shown that translating their judgements into quantities can be very difficult [Meyer and Booker, 1991].

- *Design of the Reasoning Exercises*

The second part of the knowledge elicitation was more complex, being composed of a series of reasoning exercises. The exercises proposed had two aims: gather data to be used in model construction and provide an insight about the decision-making processes. They follow the notion of protocol analysis that, as discussed by Musen [1989], consists in study the experts while they are in the process of solving problems.

The first reasoning exercise requested the experts to examine 5 bridges and discuss the differences in terms of access, cost and other factors relevant for a MRI intervention. The set of bridges was then enlarged and the experts were asked to choose the favourite mode of access to work in each of the bridges concerned, for three different situations where distinct types of activities need to be performed. On top of choosing the access equipment, the experts were asked to elaborate about the probable cost of the intervention. In the second reasoning exercise, the experts were instigated to discuss the user costs and the choice of work strategy. They were initially asked to classify 15 locations in order of relevance. They were then inquired about the importance of specific features such as hospitals, trains stations and stadiums and the importance that was given to each of these was recorded. They were then asked to estimate the impact on the users of a MRI intervention performed on each of the 15 sites. Finally, they were asked to define the work strategy that they would prefer to employ in each of the sites. The final reasoning exercise involved prioritisation of works. A map of the city of Manchester was used as a background against what pointers were fixed to indicate the position of the bridges. A second set of coloured pins was used to flag the condition of each bridge. The experts were then asked to classify the bridges in order of priority for intervention, taking into consideration the location, characteristics and condition of the structure.

- *Method of Application*

The exercises were conducted with the support of a PowerPoint presentation and some visual aids. Initially the author gave a presentation about the research. The experts were then asked to follow the presentation of the question and record their answers. Finally, they were divided in smaller groups and led trough the reasoning exercises.

- *Undertaking of Interviews.*

The interview was piloted with the assistance of two internal academic staff, and questions were refined in light of the results. The group of experts selected was interviewed in small groups of two or three. The contents of the interview are presented in the following pages.

- *Description of Experts*

An expert, as defined by Meyer and Booker [1991], is the person who has background in the subject and that is recognised by his peers or those conducting the study as qualified to answer questions. A set of persons from local authorities or research organisations involved with the inspection and maintenance of bridges that fulfil this description was selected for the interviews. Experts A to E were practitioners, bridge engineers or bridge managers linked to Local authorities in the North and Central regions of England. Experts F and G were academics, working in research areas related to the Bridge Management domain in the UK. Expert H was an academic from Brazil. Expert I was a Bridge Engineer from a local authority in Brazil while expert J was a manager in charge of Bridge Maintenance also from Brazil. Both were classified as practitioners.

- *Tabulation of Results*

Table I-1 shows the tabulation of the results of the questions posed to the experts in the first part of the knowledge elicitation exercise. The fuzzy questions were transformed using a numerical scale that associates Extremely Low with 0 and Extremely High with 10. The missing question numbers correspond to the open-ended questions.

- *List of Experts*

The list of experts consulted in the various phases of this work included:

- Dr. Antonio Grilo - University of Salford / IS Consultant
- Dr. Denise Bower - University of Manchester Institute of Science and Technology
- Dr. Leonardo Oliveira - University of Sao Paulo (USP)
- Dr. Miguel Mateus - Andersen Consulting
- Dr. Roger Cole - Lancashire County Council
- Dr. Steve She - University of Salford / Malaysian Government
- Eng. Bruno Waichel - Porto Alegre City Council
- Mr. Colin Firth - Manchester Engineering Consultancy
- Mr. David Gore - Manchester Engineering Consultancy

- Mr. Mark Wyatt - Cheshire County Council
- Mr. Martin Hutchinson - Liverpool City Council
- Prof. Francisco Gastal - Federal University of Brazil at Porto Alegre

- *Graphs*

Using some of the data from table 1, some graphics were created. Figure I-1 shows one of the most interesting graphics, illustrating how the data collected could be interpreted graphically. Adding the numerical scores that represented each fuzzy answer aggregated the results. They indicate that safety and structural integrity are on the forefront of the considerations of bridge mangers. Cost and functional considerations come after. Environmental considerations are gaining importance while public opinion is not considered so important.

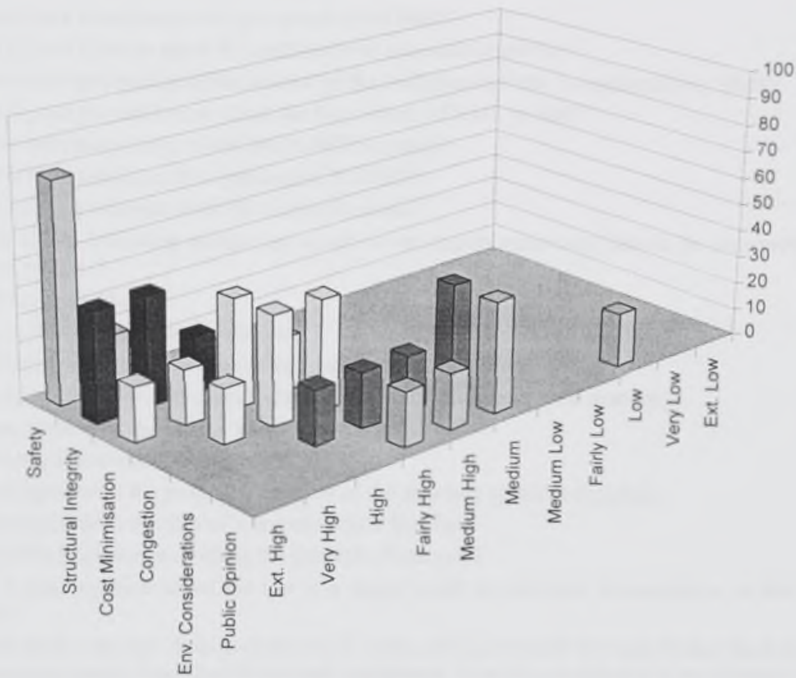

Figure I-1 – Importance given to various aspects during Bridge Management decision-making.

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- *List of Questions*

Note: as explained above, the questions were framed by the Knowledge Engineer during the interviews according with the feedback and input from the experts. The list below nonetheless gives a syntactic idea of the content and objectives of each question.

====== General Questions

1. Discuss the objectives of BM
2. Which importance would you give to each one of these factors in terms of BM.
3. How would you grade the standard of BM practice today?
4. How is BM structured in your authority?
5. How well do you think the diagram represents the process of BM?
6. Do you use a BMS?
7. Do you have experience with any commercial BMS?
8. What is your opinion about the usefulness of commercial BMS?
9. What would you reckon is the interest of the bridge authorities in implementing BMS?
10. What is your personal view about the importance of BMS in BM?
11. Do you have knowledge about the PONTIS system?
12. What is the usefulness of a system like PONTIS?
13. What are the problems faced by current systems?
14. Which of the following techniques would be an improvement and should be incorporated on current systems?

====== Diagnosis Stage

15. How do you inspect/classify defects?
16. Which techniques do you use during inspection?
17. How do you classify defects/calculate condition of bridges in your authority?
18. Do you agree with the idea of using Condition States?
19. How many CS would be adequate?
20. Do you agree with the proposed division of the structure (present diagram).
21. Do you agree with the idea of using elements/ families?
22. What is the importance of using the concept of elements?
23. What is your opinion about the use of a single grade to represent the condition of the whole bridge?
24. Do you think you can classify elements in terms of importance? Try classifying the following list according to the functional/structural importance. Now do you think it is reasonable?

====== Prognosis Stage

25. What type of risks should be considered ?
26. What are the main causes of risk in a bridge?
27. Considering the following table of natural and man-made risks, what do you consider is a reasonable level of risk of a bridge in: a) good state? b) Medium state? c) Poor state?
28. Which techniques do you use to predict the performance of a bridge?
29. What do you consider is the usefulness of each of these techniques?
30. How do you define the best technique/level of intervention to solve a particular problem?
31. Discuss the statement: "Sometimes it is necessary to intervene even if the economic analysis does not indicate that the bridge should be acted upon" .
32. How BM activities are funded at your authority?
33. If in a bridge just elements of minor importance were deteriorated which of the following policies would you prefer (do everything right away/wait/do just activities that do not interfer with traffic flow)?

====== Therapy Selection Stage

34. What is the impact of the follow ng factors in the cost of a MRI activity?
35. Do you think the costing is being done right by current systems? Do you agree with this new cost structure?
36. What is your estimation of the decrease in productivity due to the following factors?
37. What is the importance of access costs?
38. What is your assessment of the relative level of difficulty in terms of access in the following situations?
39. What I your estimation of the decrease in productivity due to the following access conditions?
40. What is the relative access cost associated with each of the following access schemes?
41. Do you make perform any type of economic analysis to choose between MRI alternatives?
42. Do you use any of the following technique to compare various MRI alternatives?
43. What do you think is the usefulness of each of these techniques?
44. Do you consider any of the following factors in you appraisal?
45. What do you think is the relative importance of these factors?
46. Do you need to prioritise MRI activities? How do you prioritise them? Which factors would make you classify a bridge repair activity as high priority if no standard classification/prioritisation method were available?
47. What is the importance of each of the following factors in terms of prioritising MRI activities?

====== Treatment Stage

48. How the following factors affect the programming of MRI activities?

====== Additional Questions

49. What is the relative importance of the following factors when developing a MRI programme?
50. Given a certain requirement, select the policy that you would support in each case

Policy 1 - wait until more work to do

Policy 2 - do part now, part later

Policy 3 - do everything now

Policy 4 - other (explain)

Case 1 Replace bearing when CS=4 (10% CS1 - 5% CS2 - 5%CS3 - 80 % CS4 - 0% CS5)

Case 2 Replace bearing when CS=4 (30% CS1 - 10% CS2 - 50%CS3 - 10 % CS4 - 0% CS5)

Case 3 Replace bearing when CS=4 (40% CS1 - 10% CS2 - 15%CS3 - 30 % CS4 - 0% CS5)

Case 4 Paint spans when CS=3 (30% CS1 -10% CS2 - 50%CS3 - 10 % CS4 - 0% CS5)

Case 5 Paint spans when CS=3 (10% CS1 - 25% CS2 - 35%CS3 - 30 % CS4 - 0% CS5)

Case 6 Paint spans when CS=3 (30% CS1 - 45% CS2 - 15%CS3 - 10 % CS4 - 0% CS5)

51. What is the importance of the following factors in your choice of work strategy/prioritisation/delaying MRI activities?
52. What is your opinion about the usefulness of the following methods to improve data management in BM?
53. How much would you support the implementation of each of them?
54. Present preliminary proposal for changes and get feedback.

Table I-1 – Tabulation of the answers collected during the first part of the expert knowledge elicitation exercise.

Subject	Question Number	Expert A	B	C	D	E	F	G	H	I	J
Safety	2a	9	10	10	10	10	9	10	10	9	10
Congestion	2b	8	9	8	7	7	7	9	8	6	5
Structural Integrity	2c	9	10	8	9	10	9	7	10	10	10
Public Opinion	2d	6	5	2	5	7	7	7	4	5	3
Environmental Considerations	2e	5	7	5	6	8	5	8	6	4	2
Cost Minimisation	2f	10	9	8	7	8	8	8	7	7	7
Performance in Bridge Management	3	8	7	8	7	8	8	5	4	3	4
Diagram Activities	5	9	8	8	8	9	8	9	8	8	8
Use BMS?	6	Y	Y	Y	Y	Y	N	N	N	Y	N
Commercial Bridge Management System?	7	N	N	N	Y	N	N	N	N	N	N
Usefulness BMS?	8a	-	-	2	-	5	8	8	8	8	8
Usefulness Particular System?	8b	-	-	-	3	-	-	-	-	-	-
Interest Authority in BMS	9	2	3	2	7	5	-	-	-	8	7
Relevance (Personal view)	10	2	5	2	7	5	8	9	8	8	7
Knowledge PONTIS	11	Y	Y	N	N	N	Y	Y	Y	N	N
Usefulness PONTIS	12	-	-	-	-	-	8	7	8	-	-
Distributed Databases	14a	7	7	8	8	10	9	7	8	6	6
On-line Data Collection	14b	7	3	2	3	3	9	9	9	7	6
Natural Language Statements/Fuzzy Reasoning	14c	8	3	5	9	9	7	8	7	9	9
GIS Interface	14d	8	7	8	9	10	9	10	8	9	8
CBR	14e	9	7	8	9	10	5	8	8	-	-
Photographs	16a	Y	Y	Y	Y	Y	-	-	-	Y	Y
Inspector description	16b	Y	Y	Y	Y	Y	-	-	-	Y	Y
Condition scale	16c	Y	Y	N	Y	Y	-	-	-	Y	Y
Drawings	16d	Y	Y	N	Y	Y	-	-	-	Y	Y
Cracking maps	16e	Y	Y	Y	Y	Y	-	-	-	Y	Y
NDT tests	16f	Y	Y	N	Y	Y	-	-	-	N	N
Condition States	18	9	8	8	8	8	10	9	9	9	9
Number Condition States	19	7	8	5	5	5	5	8	5	8	5
Concept Elements	21a	9	8	8	9	9	10	10	10	9	9
Concept Families	21b	7	7	3	8	5	10	10	10	9	5
Importance concept elements	22	8	8	8	5	10	7	8	7	8	9
Unique grade (condition index)	23	3	3	7	7	7	8	3	5	7	7
Structural Collapse	25a	10	10	10	9	10	10	10	9	10	10
Injury to Passers-by	25b	10	10	9	8	9	10	10	9	10	9
Restriction	25c	8	8	6	6	5	8	9	8	7	8
Congestion	25d	8	7	7	5	7	7	9	9	8	9
Acceptable Risk (good state)	27a	10-7	10-4	10-7	10-7	10-7	10-7	10-7	10-6	10-8	10-7
Acceptable Risk (medium state)	27b	10-7	10-4	-	10-7	10-6	10-6	10-6	10-6	10-7	10-7
Acceptable Risk (bad state)	27c	10-5	10-4	-	10-5	10-5	10-5	10-5	10-4	10-5	10-5
Use Trend Analysis	28a	Y	Y	N	N	N	Y	-	-	N	N
Use Historic Data	28b	Y	Y	N	Y	Y	Y	-	-	N	N
Use Expert Opinion	28c	Y	Y	N	Y	Y	Y	-	-	Y	N
Use Deterioration Models	28d	N	N	N	N	N	Y	-	-	N	N
Use Inspector Assessment	28e	Y	Y	N	Y	Y	Y	-	-	Y	Y
Use Engineering Judgement	28f	-	-	N	-	Y	-	-	-	Y	Y
Usefulness Trend Analysis	29a	7	9	8	5	8	8	9	8	7	6

Subject	Question Number	A	B	C	D	E	F	G	H	I	J
Usefulness Historic Data	29b	7	9	8	10	9	8	6	7	8	9
Usefulness Expert Opinion	29c	9	9	8	9	9	7	7	8	9	10
Usefulness Deterioration Models	29d	-	5	4	5	7	8	7	8	6	5
Usefulness Inspector Assessment	29e	9	9	9	9	9	8	9	7	9	9
Usefulness Engineering Judgement	29f	-	-	-	-	9	6	5	5	8	8
Cost influence amount material	34a	4	5	5	5	5	9	7	6	5	6
Cost influence haulage distance	34b	3	3	3	3	3	9	6	5	4	3
Cost influence temp. Installations	34c	3	4	3	3	5	8	5	6	5	4
Cost influence lack of space	34d	8	6	5	5	8	7	6	7	7	8
Cost influence remoteness	34e	3	4	3	5	5	9	8	6	6	5
Cost influence presence of services	34f	10	9	8	8	10	6	5	6	3	2
Cost influence environmental Restrictions	34g	9	7	5	5	8	5	8	7	3	3
Cost influence tourism considerations	34h	3	6	3	3	5	5	4	7	3	3
Cost political/legal restrictions	34I	9	8	5	5	5	5	7	5	3	5
Cost influence seasonal effects	34j	8	6	5	8	5	8	8	5	7	6
Cost influence historical importance	34k	9	5	8	8	8	-	7	7	6	8
Cost influence traffic management	34l	-	-	8	-	-	-	-	-	7	8
Cost influence commercial	34m	-	-	8	-	-	-	-	-	-	-
Cost influence traffic congestion	34n	-	-	-	10	8	-	-	-	-	-
Unit Cost Inaccurate Measure	35a	5	8	8	8	10	9	10	10	8	8
New Structure of Costs	35b	8	8	8	8	8	8	8	8	8	8
Prod. Decrease closure	36a	0	0	0	0	0	-	-	-	0	0
Prod. Decrease lane closure	36b	10	5	10	0	0	-	-	-	5	5
Prod. Decrease direction closure	36c	5	5	5	5	0	-	-	-	5	0
Prod. Decrease nocturnal	36d	15	10	15	20	15	-	-	-	15	20
Prod. Decrease off-peak	36e	10	10	10	15	5	-	-	-	10	5
Importance Access Costs	37	9	9	8	8	8	9	9	10	8	9
Difficulty access chasm	38a	7	8	8	7	8	9	8	8	7	9
Difficulty access river	38b	8	8	7	7	8	7	7	8	9	10
Difficulty access motorway	38c	10	8	7	8	10	10	10	8	8	8
Difficulty access canal	38d	7	7	5	4	7	5	4	9	8	6
Difficulty access urban street	38e	9	6	7	5	7	5	6	8	6	5
Difficulty access railway	38f	10	9	10	10	10	9	9	10	8	7
Prod. Decrease chasm	39a	10	30	25	30	40	20	-	-	30	20
Prod. Decrease river	39b	10	10	10	30	40	15	-	-	35	25
Prod. Decrease motorway	39c	10	30	10	50	75	50	-	-	30	25
Prod. Decrease canal	39d	5	10	5	20	20	10	-	-	15	20
Prod. Decrease urban street	39e	15	20	15	30	20	50	-	-	15	10
Prod. Decrease railway	39f	20	30	50	80	75	-	-	-	30	30
Cost ladder	40a	1	2	1	4	5	1	1	1	1	1
Cost moving scaffold	40b	4	2	6	3	5	5	2	4	3	4
Cost tied scaffold	40c	5	5	5	6	7	6	5	5	4	4
Cost lifting platform	40d	7	5	5	-	5	6	5	5	3	4
Cost articulated truck	40e	8	5	4	6	5	6	5	6	5	5
Cost telescopic truck	40f	8	6	5	5	5	6	7	6	6	5
Cost ropes	40g	5	4	3	5	5	5	2	3	4	8
Cost suspended scaffold	40h	7	5	8	6	8	8	6	8	7	7
Cost under-bridge unit	40I	-	9	-	-	-	-	-	-	-	-
Cost overhanging equipment	40j	9	5	10	8	8	9	9	9	10	9

Subject	Question Number	A	B	C	D	E	F	G	H	I	J
Use Economic Analysis	41	N	Y	N	N	N	N	N	N	N	N
Use dynamic network optimisation	42a	N	N	Y	N	Y	N	N	N	N	N
Use minimum cost	42b	Y	Y	Y	N	N	N	N	Y	Y	Y
Use value analysis	42c	Y	Y	N	N	N	N	Y	N	N	N
Use CBA	42d	Y	N	N	N	N	N	N	Y	N	N
Use Social CBA	42e	Y	N	N	N	N	Y	N	N	N	N
Use cost effectiveness	42f	Y	Y	Y	Y	Y	N	N	N	N	Y
Usefulness dynamic network optimisation	43a	4	4	8	9	9	8	9	9	6	7
Usefulness minimum cost	43b	8	8	9	5	7	4	3	3	5	7
Usefulness value analysis	43c	8	8	8	8	5	5	8	9	4	8
Usefulness CBA	43d	8	4	5	4	3	4	7	8	8	7
Usefulness Social CBA	43e	8	5	8	5	5	8	9	9	9	8
Usefulness cost effectiveness	43f	8	8	8	9	9	7	5	4	7	6
Consider agency costs	44a	N	Y	Y	Y	Y	Y	-	-	Y	Y
Consider user costs	44b	Y	N	N	*	*	Y	-	-	N	N
Consider environmental costs	44c	Y	Y	N	*	*	Y	-	-	N	N
Consider third-party costs	44d	Y	Y	Y	*	*	Y	-	-	N	N
Consider congestion costs	44e	Y	N	Y	*	*	Y	-	-	Y	N
Importance agency costs	45a	-	5	8	8	8	9	8	8	8	9
Importance user costs	45b	5	4	7	7	8	9	8	9	5	7
Importance environmental costs	45c	5	5	8	7	8	6	8	8	4	6
Importance third-party costs	45d	5	5	8	7	8	8	8	7	6	6
Importance congestion costs	45e	5	-	8	7	8	7	9	8	8	7
Priority traffic flow	47a	5	9	7	8	8	9	9	9	7	9
Priority defect importance	47b	8	8	8	8	10	9	9	8	8	10
Priority safety	47c	10	10	10	9	10	9	9	10	9	9
Priority politics	47d	4	3	7	7	8	6	7	5	3	5
Priority economic considerations	47e	10	3	5	5	8	9	10	9	8	9
Priority historic relevance	47f	5	6	7	8	8	5	8	7	5	7
Priority scheme complexity	47g	8	5	3	5	5	2	8	5	5	5
Priority public opinion	47h	-	-	6	6	8	-	-	-	4	5
Priority rate of deterioration	47i	-	-	8	5	5	-	-	-	-	-
Impact programming seasonal variations	48a	8	8	8	6	9	9	8	7	3	4
Impact programming weather conditions	48b	5	8	7	7	7	9	8	7	7	7
Impact programming of holidays and special occasions	48c	8	5	7	8	8	9	6	6	7	6
Impact programming budget availability	48d	-	-	7	-	9	-	9	8	10	9
Impact timing	48e	-	-	-	8	-	-	-	-	-	-
Impact restriction access (possession)	48f	-	-	-	10	-	-	-	-	-	-
Impact council policies	48g	-	5	-	-	-	-	-	-	-	-
Noise reduction	49a	9	5	7	5	8	8	7	8	5	6
Congestion	49b	6	7	8	5	9	8	9	9	9	8
Closeness city centre	49c	9	4	7	6	9	9	7	8	8	6
Importance route	49d	9	7	8	8	9	8	8	8	7	7
CDM	49e	-	-	9	9	10	8	9	9	-	-
Closeness to focal points hospitals, schools, etc	49f	-	-	-	-	9	9	7	7	5	7
Case 1	50a	3	3	2	3	3	3	3	2	3	3
Case 2	50b	1	1	1	1	1	3	3	1	1	1
Case 3	50c	1	1	1	1	2	2	1	1	1	1

Subject	Question Number	A	B	C	D	E	F	G	H	I	J
Case 4	50d	1	2	1	3	1	3	1	2	3	1
Case 5	50e	1	1	2	3	2	3	3	1	1	1
Case 6	50f	1	1	1	1	1	2	2	1	1	2
Type of work	51a	6	5	7	6	8	5	6	7	7	5
Current performance	51b	7	5	5	7	8	9	6	9	8	7
Traffic volume	51c	4	8	7	8	9	9	8	9	7	7
Money	51d	10	9	9	9	10	10	7	8	9	7
Usefulness CAD	52a	4	5	9	6	9	6	6	7	4	6
Usefulness Inspections	52b	5	5	8	8	8	8	8	8	8	9
Usefulness 3D models	52c	4	4	3	5	3	3	5	3	2	4
Usefulness photo registrar	52d	8	5	8	9	5	8	8	9	8	8
CAD	53a	4	6	5	7	5	8	6	7	5	5
Inspections	53b	5	5	2	5	4	9	7	8	8	8
3D models	53c	4	4	9	9	8	4	4	7	5	4
Photo registrar	53d	8	5	2	5	7	9	7	9	6	5

Table I-2 – Tabulation of the opinions of the experts about prioritisation of works in different locations (reasoning exercise number 3).

Case	1	1		2	2		Δ1	Δ2	3	3		Δ1	Δ2
Expert Group	1	2	Δ	1	2	Δ			1	2	Δ		
Location													
A	65	55	10	80	97	-3	15	42	30	47	-17	35	8
B	84	87	-3	83	87	-4	-1	0	25	27	-2	59	60
C	83	15	68	65	15	50	-18	0	77	55	22	6	40
D	83	45	38	66	28	38	-17	-17	76	86	-10	7	-17
E	81	81	0	15	22	-7	-66	-59	75	83	-8	6	-2
F	82	74	8	84	72	12	0	-2	95	96	-1	-13	-22
G	87	85	2	95	93	-2	8	8	45	43	-2	42	42
H	91	83	8	25	25	0	-66	-58	50	24	-26	41	59
I	75	72	3	64	63	1	-11	-9	46	45	-1	29	27
J	81	97	-16	85	82	3	4	15	100	93	-7	-19	4
K	38	35	3	-	-	-	-	-	-		-	-	-
L	72	65	7	-	-	-	-	-	-		-	-	-
M	83	94	-11	-	-	-	-	-	-		-	-	-
N	91	91	0	-	-	-	-	-	-		-	-	-
O	85	90	-5	-	-	-	-	-	-		-	-	-

Case 1 – all bridges same importance - unknown

Good agreement between experts apart from bridge C where the fact that it was an only access was only detected by group 1.

Case 2 – CS(1) = E,H / CS(2)=C,D,I / CS(3)= B,F,J / CS(4) = A,G

Again good agreement apart from bridges C and D. The variations however were very similar indicated a similar consideration of the impact of differential deterioration.

Case 3 – CS(1) = B,H / CS(2)=A,G,I / CS(3)= C,D,E / CS(4) = F,J

The variation seems to follow some general trends in terms of signal and has kept low, apart from bridges C,D and F. The relative differences showed the same tendency. Group 1 has also been more conservative in relation to bridge A.

Considerations about Bridge Utility and the determination of the Variation in Bridge Utility

To support the implementation of the concept of Bridge Utility in the new appraisal model proposed for ORIGAMI, a discussion about the determination of the variations in Bridge Utility due to different MRI strategies is undertaken in this appendix.

- *Reasons for the introduction of the concept of Bridge Utility*

As discussed in chapter 4, there are a series of factors that need to be considered when deciding on which bridge to act. The determination of the appropriateness (in this thesis expressed by the Value Index) of a MRI strategy will be dependent on the estimation of the benefits and disbenefits resulting from its adoption. The majority of these are non-monetary in nature. A suitable way of expressing them in monetary terms is by analysing their effects on a Bridge Utility Function.

Bridge Utility could be understood as a representation of the usefulness of the structure to all the segments of society. It consequently depends on the various roles played by the structure and on the importance attributed by society to each of these roles. The Bridge Utility function is an expression of the relative importance (as interpreted by the bridge manager) of these different roles. It reflects the consideration of things such as the desire for safe and easy passage, the expectancy of reliable service, time and money savings, user comfort and environmental preservation, reducing all of them to a common basis.

The format of the Bridge Utility Function is ultimately defined by the number of factors that the bridge manager (or the user of the BMS software) wants to consider and could therefore have different degrees of complexity. All BMSs must in a formal or informal way use some kind of utility function if they compare different types of benefits. The problem is that the functions normally used are very simple and consider just a limited number of elements. Frequently they are restricted to the consideration of user costs, as in the case of the DANBRO system. User costs are certainly one of the main factors to consider but this thesis argues that other factors are also important and advocates the consideration of a broader range of impacts. Moreover, not even the user costs are considered in its totality in current systems.

• *Components of Bridge Utility*

To determine the value of the MRI strategy it is necessary first to determine what makes a bridge useful. As discussed above, the usefulness of a bridge is a result of a combination of several factors. It was seen in chapter 4 that structural stability is usually considered paramount, because no one involved wants to lose the asset. It is not enough however to ensure that the bridge will not fail. Functional performance is also essential, since the main role of bridges is to allow the efficient movement of people and goods over difficult spots, as discussed in chapter 2.

Other factors must also be considered, such as the historic importance of the bridge. It was deemed adequate to collect some real data about which factors bridge experts consider relevant to include in their decision-making. To this end, the author introduced in the Knowledge Elicitation Interview some questions to determine how bridge managers attributed importance to the needs of a certain bridge (the summary of results is available in Appendix I). Besides structural soundness and user safety, the experts expressed the desire to take into consideration the historical value and the functional importance of the bridge. They reckoned that the later two factors are not being adequately addressed by current decision-making procedures in the existing Bridge Management Systems. The experts also considered important to verify the strategic role of the bridge. This can be seen as a reflection of the fact that a higher degree of importance is normally given to bridges that allow the passage of abnormally heavy traffic trough the network or that a higher priority is given to bridges that are the only access to certain locations. The experts additionally commented that, in view of the pressure from the central government, the avoidance of congestion is a topic that is gaining importance but they did not seem to give much importance to the consideration of user opinion or political factors. The utility of the bridge can be therefore understood as:

$$BU = f(\text{safety, historical importance, functional characteristics, strategic importance}) \quad \text{(Eq. II-1)}$$

Hypothetically, a bridge in perfect condition would be at the maximum utility. The compromise of its function or the decrease in safety would reduce the utility. Other factors could also reduce utility, like a change in traffic patterns that would alter the functional or strategic importance of an structure or the change in aesthetic or cultural values of society that would lead to a redefinition of the bridge historic importance. This will however not be explored in this thesis. By analysing the impact of different MRI strategies in the Bridge Utility function it is possible to estimate a monetary value for the benefits. It is the changes deriving from deterioration and maintenance that are of interest. It is essential therefore to estimate the variation in bridge utility caused by them, as follows.

• *Variations in Bridge Utility*

The main effect of MRI strategies in the bridge utility is related to the reduction of the negative consequences of deterioration or obsolescence. Based on the examination of expert opinions and on the insights gained during the analysis of bridge aims discussed in chapter 4, the author concluded that bridge utility would be affected by deterioration in three main ways:

- the loss of the asset
- the restriction of use
- the deterioration of service

The consequences of each of these occurrences are described in figure II.1

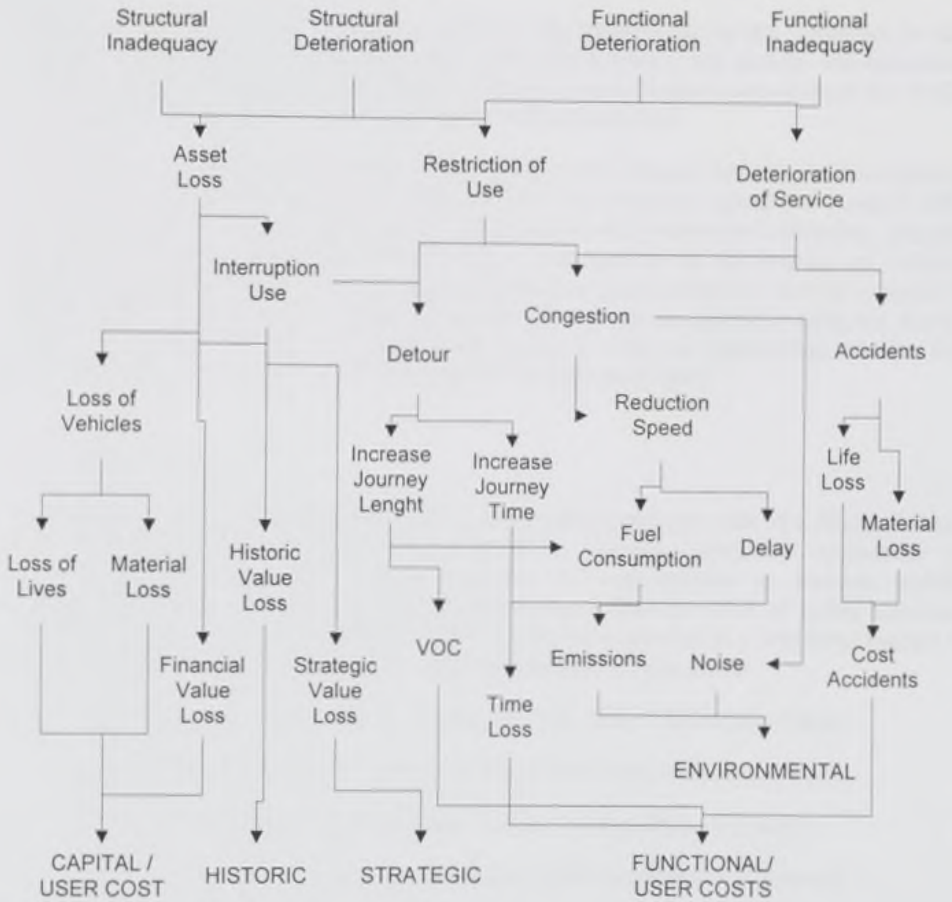

Figure II.1 – Summary of the deleterious effects of deterioration and inadequacies.

As seen in the figure, the consequences could be divided in seven major areas:

- capital loss represented by the loss of the asset
- user costs involved with the loss of the asset
- historic loss because of the loss of the asset
- strategic consequences of the loss of the asset
- functional cost because of the absence of the asset
- user costs because of the restriction of use or deterioration of service
- environmental cost of the restriction of use or deterioration of service

The first five are related to the loss of the asset and depend on the variation in the probability of failure. The other two are effects of the compromise of function. Using the notation adopted in chapter 5, the variation in bridge utility will therefore be represented as:

$$VBU = \Delta P_f * (BV + UCC) + \Delta UC + \Delta EC \qquad \text{(Eq. II-2)}$$

The capital, historic, strategic and functional losses are combined in a term denominated Bridge Value, as described in chapter 4. The UCC represents the user costs (or external costs) at collapse. These are fixed for a certain bridge at a certain time (the functional importance can vary over time due to the natural increase in the number of vehicles using the bridge). The parameters ΔP_f, ΔUC and ΔEC refer respectively to the variations in the probability of failure, the variation in user costs during normal use and the environmental costs that are caused by a change in the Condition State of a particular element due to the application of a specific MRI strategy (that could be do-nothing).

The first part of equation II-2 will be denominated as the Value at Risk. A similar approach was used by Penning-Rowsell et al. [1992] to make an economic appraisal of coastal cliffs enhancement projects. The second part of the equation was denominated Disutility, because it is composed by elements that reduce utility and depends on the number of vehicles detoured, the reductions in speed due to deterioration or speed restriction and the increase in the number of accidents. The monetary impact of these can be estimated using the similar methods to those adopted to estimate the External Cost of Intervention (ECI). The determination of the components of equation II-2 is discussed below

- *Bridge Value*

The general public is naturally reluctant to accept even a minimal risk of a bridge failure. However, achieve this absolute level of safety is virtually impossible, technically or economically. Therefore, the balance between the requirements to maintain public confidence and the available resources for ensuring a feasible level of safety becomes primarily a political decision. [OECD, 1976]. To take this decision in a structured manner it is necessary to estimate the value embedded in the bridge, as seen above.

Four components were considered as forming the main bulk of the Bridge Value:

- Capital value: which can be represented by the asset value as discussed before.
- Functional value: depend on the number of users and the alternative routes.
- Historical value: depend on the age, uniqueness and relevance of the structure
- Strategic value: determined by the position, functional role and strategic importance of the bridge in the network.

The first two can be estimated directly in monetary terms. The Asset Value can be calculated using the replacement costs of the elements of the bridge while the functional cost can be determined using the results of the determination of the impacts of adopting a total closure work strategy.

Attempts to estimate the other two value components directly in monetary terms could also be made. Considering however that this would be a complex exercise and that a large degree of precision is not deemed necessary for the type of strategic decisions being taken, the author proposes the adoption of a simpler approach. This would consist in the definition of the historical and strategic value components as a function of the Asset Value (AV). The Historical Value for example would be given by:

$$HV = v_h AV \qquad \text{(Eq. II-3)}$$

Where: v_h is a majoring factor that varies with the historic relevance of the bridge.

Suitable majoring factors can be estimated using valuation methods such as Revealed Preference, discussed in chapter 5. The author carried out an exercise to obtain a preliminary estimate of these values. In the exercise, an expert was given the choice between rehabilitating a bridge that was classified as historically important or "n" other bridges that were similar in everything but were considered of normal (i.e. "low") historical importance. By varying the value of n and discovering the neutral point it was possible to have a estimate of the relative value attached by the expert to the historical importance of a bridge. Similar procedures were carried out to define values for the strategic majoring factor. The results are presented in table II.1.

Table II.1 - Majoring factors used to determine the Bridge Value components.

Relevance	Strategic	Historical
	v_{st}	v_h
Low (normal)	1	1
Medium	1.5	2
High	5.6	9

The values were then used to create a function that relates the majoring factor to the strategic and historical relevance expressed as a linguistic statement in a universe of discourse going from "extremely low" to "extremely high", as discussed in chapter 8. Figures II.2 and II.3 show the relations established.

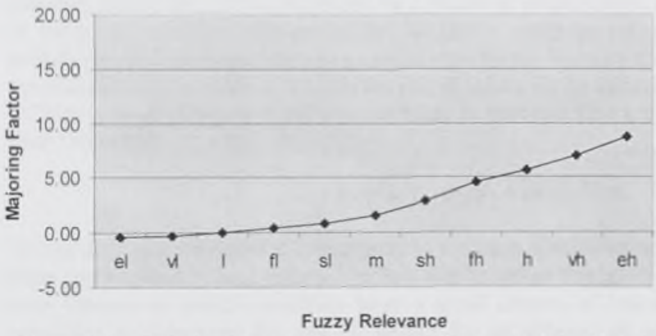

Figure II-2 – Relation between the majoring factors and the historic relevance.

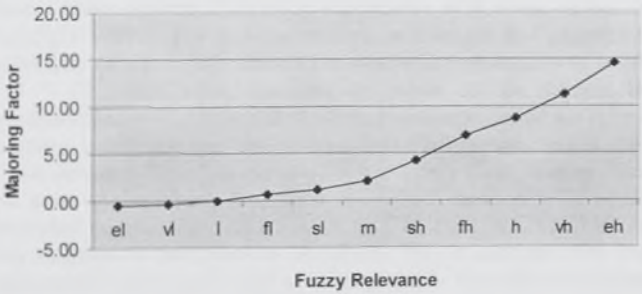

Figure II-3 – Relation between the majoring factors and the strategic relevance.

Even highlighting the fact that the values produced by these functions should be seen as mere approximations, it is recommended that they should be considered in the model. As emphasised by Brent [1996], there is nothing "scientific" about making value judgements implicitly. To comply with the principle of clarity it is necessary to make the system of values that is guiding the decision-making process very clear.

The author believe that the use of this model would allow all parties involved to understand how the decisions are being reached and would stimulate the discussion of the validity of the value judgements made. This open discussion of the values used to determine the bridge value to be used in the appraisal would lead to improvements in the models and in the establishment of better decision-making procedures. To use the functions above in order to determine a majoring factor it is necessary however to make an estimate of the relevance of the structure for each of the two aspects: historic and strategic. The historic relevance can be calculated from the characteristics of the bridge or instinctively estimated by the user. The strategic relevance is not so easy to assess. The author investigated the possibility of developing a model to express the strategic relevance, reported in Appendix VII.

- *Probability of Failure (Element)*

To determine the Value at Risk it is necessary to define how the probability of failure of the bridge varies with the deterioration of the condition of an element. The first step nonetheless is to analyse how the probability of failure of the specific element varies with changes in its Condition State. The chance of failure is naturally expected to grow with the worsening of the Condition State. Since it was advocated that advanced systems should adopt a probabilistic approach for condition forecast, the Condition State at time t will not be certainly know, but will be expressed by a vector of probabilities, as discussed in chapter 2. In these circumstances, the probability of failure could be calculated by multiplying the probability of an element being in a certain state by the standard risk of failure that would be associated with that state. If Rf(x) is the risk of failure for an element in condition state k and $PCS_k(t)$ is the probability of the element being in state k at time t, the probability of failure at time t would be:

$$P_f(t) = \Sigma_k[Rf(k) * PCS_k(t)] \qquad \text{(Eq. II-4)}$$

To use the equation above it is necessary to establish a relationship between each Condition State and a certain risk of failure. The first step to define this relationship is to recognise that even bridges in perfect condition have a small chance of failure. This means that it is necessary to determine the risk of failure for an element in perfect condition (CS=1). Theoretically, this chance will be different for each type of element and mode of failure. For structural elements, the failure probability should be around 10^{-8}, according to opinions elicited from experts. This is in accordance with some values calculated by Estes and Frangopol [1996]. For a concrete deck in a bridge in Colorado, they estimated a failure probability of $1.77 * 10^{-8}$ while for a column the probability of crushing varied from 3.27 to $5.27 * 10^{-9}$. Meanwhile, the risk of failure for an element in a failed state would hypothetically be 1, although it might be possible to define the failed state as the point where the safety coefficient becomes smaller than 1 but the structure is still standing. The evolution of risk between these two extremes is not totally clear because there is a lack of studies on this area, as discussed in chapter 6. While more detailed studies are not available a simplified approximate risk function will be used in ORIGAMI to estimate these values. This function is described in Appendix VII. It assumes that the risk of failure varies exponentially between Condition State 1 and 5. The risk at Condition State 5 is determined using data extracted from PONTIS

- *The Probability of Failure (Bridge)*

The appraisal of MRI alternatives using the new model proposed will be concerned with selecting actions to correct individual problems in certain elements of the bridge. However, the utility function considers the bridge as a whole. It is necessary therefore to establish the relationship between the probability of failure of a certain element and the safety of the entire bridge. Various researchers have discussed how to combine individual probabilities of risk for bridge components into a combined risk of failure for the whole system [Thoft-Chistensen, 1997; Moses, 1996]. Simplified series or series-parallel models have frequently been used [Estes and Frangopol, 1996] to represent the bridge system.

Since the role of the P_f in the appraisal model is not to determine safety but to provide a notional idea of the chance of failure, a simplified series model will be used in this work. The idea of interpreting the probability of failure in a notional and comparative way is discussed and justified by Moses [1996]. It is important to remember that the failure of different bridge elements will have distinct consequences in the safety or performance of the structure. To express this a weight factor will be used, similarly to what was advocated by Gastal et al. [1995]. An exercise was carried out with experts during the development of this thesis to try to extract the data necessary for the establishment of such a relative scale of weights. During the knowledge elicitation exercise questions were posed to the experts about the relative importance given by them to each element in terms of the safety and the performance of the bridge. The results are shown in table II-2. It is interesting to notice that they are consistent with the values adopted by Klein et al. [1993].

Table II-2 – Relative importance of bridge elements according to experts.

Element	Importance (structural safety)	
	Distribution of Opinions	Mean Value
Deck	Extremely High (50%) High (50%)	Extremely High
Bearings	Very Low (17%) Medium (17%) Fairly High (17%) High (49%)	Slightly High
Foundations	Medium (50%) High (17%) Very High (17%) Extremely High (17%)	Fairly High
Pavement	Extremely Low (50%) Very Low (33%) Medium (17%)	Very Low
Abutments	Low (17%) Medium (17%) Fairly High (33%) Extremely High (33%)	Fairly High
Joints	Extremely Low (17%) Very Low (32%) Slightly Low (17%) Fairly High (17%) High (17%)	Low
Girder	Extremely High (66%) Very High (17%) High (17%)	Extremely High
Columns	Extremely High (66%) Very High (17%) High (17%)	Extremely High
Arch	Extremely High (50%) High (17%) Fairly High (33%)	Very High

• *User and Environmental Costs*

Three other factors apart from the Bridge Value and the Probability of Failure must be calculated: the User Costs during normal operation (UC), the Environmental Costs during operation (EC) and User Costs at Collapse (UCC). To implement the Bridge Utility Function (and consequently allow the use of the novel appraisal model) the variations on these costs due to changes in the bridge condition must be modelled. The models proposed will be based on the estimation of the monetary impacts of the deleterious effects indicated in figure II.1. The models themselves are discussed in Appendix VII.

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Valuation of Non-Monetary Impacts

In the main body of this thesis the author presented an argument for using an economic (monetary-based) appraisal model for decision-making in advanced BMS despite the non-market nature of several of the impacts associated with Bridge Deterioration and Maintenance. This appendix presents some considerations about the monetary valuation of some important non-market impacts associated with Bridge Management, such as time, human lives and atmospheric emissions.

A review of the literature was carried out to identify a sensible range of monetary values to attach to such effects. From a purely economic point of view, these values may be considered arbitrary but they give an idea of the order of magnitude for these costs and are essential to allow the introduction of a social and holistic decision-making structure in advanced systems, as emphasised in chapter 4.

- *Atmospheric Emissions*

Atmospheric emissions are one of the most important environmental effects of road transport. According to the Royal Commission on Environmental Pollution [1995], road transport is the most important source of airborne pollutants outside industrial regions. Traffic emissions have therefore a deleterious effect on society and it is necessary to provide an estimate of these impacts in monetary terms. Monetary values for atmospherics emissions are not easily defined but need to be considered if a proper decision-making process is to established, as remarked by the Royal Commission on Environmental Pollution [1995]. To establish suitable monetary values for these effects the author reviewed some previous studies on the topic including Hueting [1995]; Saelensminde [1995] and Hanley et al. [1997].

Hesselborn [1995] reported one of the most relevant studies. It discussed some fiscal instruments used in Sweden to internalise motor vehicle air pollution effects and explained how monetary values for these effects were calculated. Table III.1 shows the values obtained, in Swedish Kronas, Euros and Sterling Pounds. The values for sulphur and carbon dioxide emissions were derived from the income tax on emissions (introduced by legislation in 1991), and are defined to represent the social marginal cost of these emissions. The value for nitrogen oxides corresponds to the tax applied to emissions of industrial furnaces and represents the cost of implementing measures for the abatement of such pollutants. The value for hydrocarbons was chosen to reflect the assumption that they are half as damaging as nitrogen oxides.

Table III.1 - Monetary values for the cost of atmospheric emissions used in Sweden.

Emission	Price per Kg		
	SKr (Base: 1996)	ECU (Base: 1996)	£ (Base:1998)
CO2 (Carbon Dioxide)	0.36	0.042	0.035
SO2 (Sulphur Dioxide)	15	1.74	1.42
Hydrocarbons	20	2.32	1.89
NOx (nitrogen Oxides)	40	4.65	3.78

To check the adequacy of this data in relation to other countries the author compared it with some data presented by Royal Commission on Environmental Pollution [1995]. According to it, the annual cost due attributable to road transport due to air pollution would vary between 2.4 and 6 billion pounds a year in 1994 (approximately 2.8 to 7 billion in 1998 prices). Using the emission matrix presented in table III.2 for an average car [Volkswagen, 1995], the cost per km was estimated. Considering a predicted 450 billion vehicle-km per year, the final result would be that the cost of atmospheric pollution in 1998 would be of the order of £4.95 billion. This value is well inside the interval given by the Royal Commission.

Table III.2 - Average emissions of a car

	Emission (g/km) – petrol	Emission (g/km) - diesel
CO2 (Carbon Dioxide)	240	167
SO2 (Sulphur Dioxide)	0.02	0.02
Hydrocarbons	0.65	0.145
NOx (Nitrogen Oxides)	0.37	0.67

The values of table II-1 are however considered conservative because they are based on taxes effectively implemented and do not take into consideration all the negative effects of the emissions. The real costs of the environmental pollution are probably higher. The Royal Commission itself estimates that just the cost of climate change costs in the UK could reach £4.20 billion/year. Adding this to the highest estimate of costs and considering the lower estimate of traffic would more than double the cost.

The UK Environmental Accounts [1998] estimates that the effects on atmospheric pollution are annually worth around 45,381 million pounds. At the same time, it points out that the domestic transport activities (mainly road and rail) respond by around 89% of the CO emission, 51.3% of the black smoke (particulates) and approximately 18% of the acid rain and greenhouse gases.

The author recommends that the user should be allowed to chose a value in certain range provided by the computer. Values on the range of £0.10 to £1.00 per litre of petrol seem to be justifiable with the information available at the moment. The author however stresses the need for further studies to determine more adequate values to use to assess the monetary value of the atmospheric emissions. In the UK some measures are being planned that may help assess the impact of cars in the environmental conditions. Roadside tests to check vehicle emissions are being considered by several local authorities, such as Westminster, Bristol, Middlesborough, Birmingham and Glasgow [Automobile Association, 1998]. These can be used to draw a more accurate picture of the amount and distribution of pollutants being produced by road traffic. Studies are also being carried out to establish better causal relationships associating emissions and damages to human health and the environment [Hanley et al., 1997].

- *Time*

Various studies have been directed at associating a value with the time lost in the course of driving in congested conditions [Bruzelius, 1979; Hague and Accent, 1996; Wardman and Mackie, 1997].

An extensive study of the value of time was made by a Consortium including the MVA Consultancy, The Transport Studies Institute at Leeds University and the Transport Studies Unit at Oxford University [MVA et al., 1994]. The results showed that the time value is not easily determined and tends to vary with income and transport mode.

Another important factor when discussing the topic of valuing time is the determination of the purpose of the trip. According to Layard and Glaister [1994], for time saved in the course of work the problem of valuation is simpler because the cost can be estimated from the reduction on the worker's output, which is roughly measured by his wage. Despite this being an accepted practice, there is some controversy nonetheless about the validity of taking the wages as a reference for the time value. Some authors suggest that other factors must be included in the picture, such as the fact that travelling instead of working can cause some excess psychic (dis)satisfaction.

It has become clear from the analysis of the studies discussed above that the value of time is not a fixed quantity and that average values will need to be established to represent it. Despite the inherent difficulties in estimating a monetary value for time, the studies are able to provide a general understanding of the factors that influence the value attributed to time and helped determine the order of magnitude of this value. This is very important to the examination of MRI options in Bridge Management because both interventions as well as the deterioration of the condition of the structure can cause congestion and delays.

The comparison of various studies undertaken by MVA et al. [1994] provided evidence to the effect that the value of in car-time would be around 5p/min for commuting, 8p/min for business trips and 7p/min for leisure time. For train journeys the value of time would be around 5p/min for commuting but would rise to10 p/min for leisure. Waiting time was valued more highly at approximately 11.5p/min. Hague and Accent [1996] meanwhile establish an average value of 5.4p/min for commuting time and 4.3p/min for leisure time. Wardman and Mackie [1997] carried out a comprehensive investigation of 105 studies. Reporting it, Mackie [1998] described that the investigation pointed to a mean value of 4.85p/min for commuting time and 5.11p/min for leisure time.

These results are generally compatible, despite the slight variations. In general terms, a value of 5p/min could be assumed for commuting time and 5.5p/min for leisure time (approximately the average of the results discussed above). The value of time for business time will be established at 8p/min. These are conservative estimates but they are well inside the range of values described in the studies reviewed.

Considering that for private cars in average 20% of the trips are commuting to work, 19% shopping, 32% are business, personal business or education and 29% are leisure [Royal Commission on Environmental Pollution, 1995]. Defining shopping trips as a type of commuting, the average value of time for a private car could be calculated as:

$$\text{Value (time)} = (0.39*5 + .32*8 + .29*5.50) = 6.10\text{p/min} \qquad \text{(Eq. III-1)}$$

If the existence of 0.21 passengers is assumed according to the recommendations in the QUADRO manual at the value of their time is taken as 80% that of the driver, the average value of time for an average car would be approximately 7.12p/min.

The QUADRO software also contains indications about the value of time for an average car. It estimates the value of leisure (non-working time) at 3.7p/min. The cost of working time is assumed as varying depending on the type of vehicle and passenger (the time of drivers is valued at a higher rate) from 10.94p/min for a driver/passenger of a light goods vehicle to 17.4 p/min for the driver of a private car). Considering an average of 1 driver and 0.21 passengers and a work/non-work time spit of 16.7%/83.3%, it estimates that the value of time for an average car would be approximately 7.12 p/min (value corrected to 1998 prices). As can be seen despite the differences in the individual value of time, the final value is compatible with the one calculated above. It is also in the same range of the 6$ an hour adopted in the U.S. by the Wisconsin DoT [WisDot Homepage, 1997] for representing the delay cost, which corrected to 1998 values in pounds would result in 6.5p/min (the WisDot emphasises that its value is considered as slightly conservative).

Given this examination, the author concluded that it would be adequate to assume the following values as an approximation of the value of time to be used in ORIGAMI (and on the validation exercises):

Average Car: ≈ 7.04 p/min

Light Goods Vehicles: ≈14.22 p/min

Heavy Goods Vehicles: ≈ 15.25 p/min

Passenger Service Vehicles: ≈ 49.55 p/min

Users must be stimulated to study and discuss the adequacy of these values to their own realities and should be allowed to change them at will.

- *Life*

According to Hanley and Spash [1993] it is theoretically possible to estimate either the marginal benefit of keeping someone alive or the marginal costs of someone dying. They argue that "whilst such calculations might seem repugnant to many, the valuation of human life turns out to be crucial for the analysis of various projects".

The simplest method to value a life is the Human Capital approach, which estimates the value of a statistic life based on the earnings foregone by an individual due to the interruption of his life. Using 1981 values for the U.S., Forester [1984] calculated the monetary value of a life as $527,200, assuming a national average earning of $15,946, an average age of 33.5 years, an average expected lifetime of 65 years and a discount rate of 0.5%. Using the concept of the net contribution to the economy instead of the total earnings foregone (which would imply the deduction of the consumption incurred by the person during his lifetime) and assuming a 30% consumption rate (indicated by Brent [1996] as coming from studies from the Department of Labour), the value would fall to $369,040.

The main problem of the Human Capital method is that it is based on the effect on society and ignores the preferences of the individual, therefore going against the precepts of a CBA analysis. To counter this effect, Schelling [1968] (apud Layard and Glaister, 1994) proposed the concept of statistical death. This involves dividing the possible number of deaths by the total population and establishing a theoretical risk of loss of life. By considering what individuals would be willing to pay or receive to reduce or increase the risk they are subjected to, this approach provides the mechanism for measuring the value of life from an individualistic point of view, according to Brent [1998]. Attempts to extract this value are usually based on the theory of equalising differences [Rosen, 1994], which justifies the existence of wage differences similar to risk premiums that are applied to riskier forms of employment. Other formulations, for example comparing the increased risk against the time lost because of the use of seat belts are also used. Two such exercises, used by Forester [1984] to demonstrate that the introduction of the 55-mph limit in highways in the U.S. was not cost-effective, came up with a similar value for a life around the threshold of $390,000.

Correcting these values to 1998 values using the American consumer price index and transforming them to pounds using the exchange rate of 1£ = 1.67 $, the value of a human life would be approximately £380.000 for the net human capital approach and £400.000 for the equalising differences. These values are relatively conservative when examined against the results compiled by Jones-Lee [1994]. Analysing several studies he established four intervals and calculated the percentage of studies that indicate the value of life to be in that interval. Using just the more reliable estimates and adjusting the values for 1998 using the retail price index, these intervals would resemble the ones showed in table III.3 below.

Table III.3 - Distribution of estimates of the value of a statistical life (Based on Jones-Lee, 1989). Values corrected by the RPI to June 1998.

	Number of Studies	Percentage
Less than £400,000	1	6.3
Between £400,000 and £800,000	4	25
Between £800,000 and £1,600,00	1	6.3
More than £1,600,000	10	62.4

The table suggests that the value of a statistical life could be assumed to be in excess of £400,00. Jones-Lee argues that, because external costs of the loss of life (hospitals, etc) are not being considered in these estimates, it would be possible to make a respectable case for the adoption of a higher value, in excess of £2,000,000. He argues that a figure of £3,000,000 (in 1998 values) could well be warranted. Markandya and Milborrow [1998] recently reported that in the Green Accounting Project a value of around £2,400,000.00 was adopted to represent the statistical life.

Considering the data above and reflecting that the present work is interested in the order of magnitude of the results, the author decided to adopt an intermediary view and establish the value of £1,000,000 for the statistical life. This was the value used in the calculations performed. It was also the one suggested for adoption as a standard choice in ORIGAMI. Provisions should nonetheless be made in any advanced systems to allow users to choose other values, as it was done in the prototype.

- *Noise*

The value of noise is associated with the disruption caused by it. This will in turn depends on loudness and the interference provoked in human activities. As registered by Koushki [1993], this can be significant. Noise is generally expressed in terms of its intensity (W/m2) or sound pressure (usually given in μbars), using the decibel logarithmic scale.

Various noise descriptors can be used to describe the noise intensity. The FHWA [1995a] uses the L10 and Leq descriptors in its noise abatement procedures. The former is the noise level exceeded 10% of the time in the noisiest hour of the day. The latter is the constant, average sound level, which over a period of time contains the same amount of sound energy as the varying levels of traffic noise registered in practice. The L10 is a statistical descriptor that is easy for most people to determine and understand. The Leq meanwhile is harder for inexperienced people to understand, but it has the advantage of being more reliable for low-volume roadways. It also permits noise levels from different sources to be added directly to one another for inclusion in noise analyses. According to the FHWA, Leq values for typical traffic conditions are usually about 3 dBA less than L10 values for the same conditions.

Table III.4 gives the acceptable boundaries of noise using both descriptors. This can be seen as indirectly indicating the acceptability of noise and will be use in the noise sensibility model discussed in Appendix VII. The dBA means decibels measured according to instrumentation scale

A [Peterson & Gross, 1979]. Either L10(h) or Leq(h) (but not both) may be used on a project but the discussions in this thesis will be carried out considering the Leq. For the simplified purposes of this thesis just the external values of noise will be important.

Table III.4 - Noise Abatement Criteria (NAC). Maximum acceptable Hourly A-Weighted Sound Levels (in dBA). (Adapted from FHWA, 1995a).

Activity Category	Leq(h)	L10(h)	Description of Activity
A	57 (Exterior)	60 (Exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 (Exterior)	70 (Exterior)	Picnic area, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 (Exterior)	75 (Exterior)	Developed lands, properties or activities not included in Categories A or B above.
D	-	-	Undeveloped Lands
E	52 (Interior)	55 (Interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals and auditoriums.

According to the table, if the noise is higher than 67 dBA in sensitive area or 72 dBA in normal houses, the impact would be significant enough to force the consideration of abatement measures. Below that the noise can still be an irritant but there is no imposed need to consider its abatement.

While these measures are more important during the construction or improvement of structures than during its maintenance (since the level of noise usually does not change significantly after it), they are useful to help establish parameters to determine the noise impact.

The FHWA has developed a model to accurately forecast highway traffic noise levels and produces national averages of vehicle emission levels to support it. State highway agencies either use this model for highway traffic noise analysis or have developed alternative models based upon the same methodology. If potential traffic noise impacts are identified, noise abatement measures must be considered and implemented if it is found that doing so is both reasonable and feasible. The views of the impacted residents are a major consideration in reaching a decision on the reasonableness of abatement measures to be provided. When noise abatement measures are being considered, every reasonable effort is made to obtain substantial noise reductions.

There is no mandated definition for what constitutes a substantial increase over noise levels existing in an area. However, variations between 10-dBA and 15-dBA are normally accepted as "substantial". The logarithmic scale used means that a rise of 10 dBA is equal to a doubling on the level of the loudness, a change that is easily perceived by the public. The FHWA advocates that increases around 5-6 dBA should already be considered as considerable. Sliding scales can be used that combine the increase in noise levels with the absolute values of the noise levels, allowing for a greater increase at lower absolute levels. Two points should be kept in mind:

- any reduction will improve the noise environment in such areas as annoyance, speech interference, task interference, etc.
- until the level reaches a very low level (about Leq = 55 dBA), the noise environment will continue to be dominated by traffic noise that is clearly audible. [FHWA, 1995b]

According to the FHWA [1995b], the costs of noise abatement measures are not expected to exceed U$20,000 per residence, including any safety and drainage features included specifically due to the abatement measures. This value can be used as a reference of the willingness to spend of the government to solve noise problems. Results from Saelensminde [1995] about the WTP of individuals suggest that they would not be willing to fund such expenditure. The author verified by examining such results that a reference value for the reduction of noise can not yet be well-defined and that further studies are necessary in this area. In the short term however the author decided to adopt the £12,000 figure as a reference for the model developed in Appendix VII.

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Appendix IV

Data Object Descriptions

This appendix describes the main objects suggested for adoption in the first version of ORIGAMI to support the Appraisal sub-system. It focuses on the data objects, showing a list exemplifying the type of properties that would be attributed to each of them.

- *Data Objects*

The set of Data Objects proposed for implementation in the initial version of ORIGAMI is described below. The information displayed includes the name of the main properties and their description and type. Additionally, it presents the Rule Parameter Identification Code (RPIC), which serves as a unique reference to each of the respective properties of the various objects during the creation and processing of rules.

The names used for the object properties are user-friendlier than the ones used to codify the bridge characteristics in the databases. For example, *DirSuf* is represented by its full denomination, Direction Suffix, in this way improving clarity, as proposed in chapter 7.

To further improve clarity the objects could be provided with internal methods to translate the numerical codes used in the databases into more easily understandable strings or linguistic variables. It is possible to do this without serious consequences in terms of storage space because the objects just need to store the translation procedures and not the data. Even if internal variables were used to store the translated values, no problems would be likely to occur because few objects of each type (usually jut one) would be active simultaneously. When this is possible the last column of the table shows the suggested types for the internal and external variables.

It is important also to highlight that some of the properties described are direct reflections of the values in the database while others are the results of other calculations made at run-time. The *Bridge.Custodian* or the *Bridge.Trunk_Network* parameters for example would be determined at run-time using the GIS component.

Finally, it is interesting to remark that while some properties are crisp in nature, they will have to be fuzzified to be used in the rules. It is for example the case of *Activity.SetupCost*. In these cases the Rule object will retrieve the membership functions established by the author to that parameter and interpret it. The result will be a vector indicating how much a certain cost fits into each of the fuzzy categories (extremely low to extremely high).

- *Bridge (data object)*

Property Name	RPIC	Description	Type
ID	1	Bridge identification code	Variant
Denomination	2	Official or technical denomination of the bridge	Variant
Common_Name	3	Usual or popular name	Integer/String
District	4	Local authority or district where the structure is located	Integer/String
County	5	County where the structure is located	Integer/String
Owner	6	Bridge owner	Integer/String
Custodian	7	Agency responsible for the maintenance of the structure	Integer/String
Location	8	Description of the Location	String
Latitude	9	Latitude	Degrees
Longitude	10	Longitude	Degrees
Milepost	11	Milepost	Single
Highway_System	12	Highway system to which the bridge belongs	Integer/String
User_System	13	User defined system to which the bridge belongs	Integer/String
Type_Structure	14	Type Structure (0-Culvert/1-Arch/2-Segmental/3-Presstresed/4-boxgirder/5-Suspension)	Byte/String
Year_Built	15	Year built	Integer
Year_Reconstructed	16	Year reconstructed	Integer
Historical_Relevance	17	Historical relevance expressed in fuzzy terms	String
Strategic_Relevance	18	Strategic relevance expressed in fuzzy terms	String
Link _On	19	Code indicating the traffic link carried by the structure	Variant
Direction_Suffix	20	Directional suffix indicating main orientation of the bridge in relation to the authority system of references	String
LOS	21	Designated Level of Service (mainline, ramp, etc.)	Integer/String
Toll_Fac	22	Tool charge	Boolean
Functional_Class	22	Indicates functional class	Integer/String
Gas_Service	23	Presence gas services	Boolean
LVElec_Service	24	Presence low voltage electrical services	Boolean
HVElec_Service	25	Presence high voltage electrical services	Boolean
Water_Service	26	Presence water services	Boolean
Tel_Service	27	Presence telephony services	Boolean
Cable_Service	28	Presence Cable or TV Services	Boolean
Oxygen_Service	29	Presence oxygen services	Boolean
Other_Service	30	Presence other services	Boolean
DesignLoad	31	Design Load specifications	String
Restriction	32	Indicates if the bridge was posted or closed	Boolean
Restriction_Weigth	33	Indicates maximum weight allowable	Single
Restriction_height	34	Indicates Maximum height allowable	Single
Inventory_Weight	35	Allowable weight designated in bridge inventory	Single
Number Spans	36	Number spans	Byte
Noise_Sensibility	37	Sensibility to noise calculated using the GIS	String

- *Element (data object)*

Property Name	RPIC	Description	Type
ID	100	Element Identification Number	Variant
Bridge_ID	101	ID of the bridge to which the element belongs	Variant
Span_ID	102	Span of the bridge to which the element belongs	Variant
Code	103	Element Code (according to the PONTIS classification or a similar one)	Integer/String
Family	104	Element Family (Column, Beam, etc.)	Integer/String
Description	105	Description of the element	String
Height	106	Element height	Single
Width	107	Element width or diameter	Single
Access_Height	108	Height for access to the element	Single

Free_Lateral_Space	109	Free lateral space for working on the element	Single
Preferred_Access	110	Preferred Mode of Access	Integer/String
Risk	111	Risk of Failure	Double
Condition Index	112	Combined Condition Index	Single
Inspection_Year	113	Year of last inspection	Integer
Inspection_Code	114	Code identifying last inspection	Variant
TTC12	115	Time to change CS 1 / CS 2	Integer
TTC23	116	Time to change CS 2 / CS 3	Integer
TTC34	117	Time to change CS 3 / CS 4	Integer
TTC45	118	Time to change CS 4 / CS 5	Integer
TTC5F	119	Time to change CS 5 / failed	Integer
TP(1,2)	120	Transition Probability CS 1 / CS 2	Single
TP(2,3)	121	Transition Probability CS 2 / CS 3	Single
TP(3,4)	122	Transition Probability CS 3 / CS 4	Single
TP(4,5)	123	Transition Probability CS 4 / CS 5	Single
TP(5,F)	124	Transition Probability CS 5 / failed	Single
Pct_State(1)	125	% element in Condition State 1	Single
Pct_State(2)	126	% element in Condition State 2	Single
Pct_State(3)	127	% element in Condition State 3	Single
Pct_State(4)	128	% element in Condition State 4	Single
Pct_State(5)	129	% element in Condition State 5	Single
Pct_Failed	130	% element in Failed State	Single
ReplacementCost	131	Cost of replacing the element	Currency
Probability Failure	132	Probability failure time T0	Single
Environment	133	Environment type where the element is located	Byte/String

- *Span*

Property		Description	Type
Name	RPIC		
ID	201	Identification code of the span	Variant
Direction	202	Direction of span	Integer/String
Skew	203	Skew angle with normal line of roadway	Integer
Deck_Width	204		Single
Flared	205	Indication of variation in width	Integer
Use_Under	206	Type of obstacle surpassed by the structure (river/ highway, road)	Integer
Vert_UnderClearance	207	Minimum vertical clearance	Single
Vert_OverClearance	208	Minimum vertical clearance over span	Single
Depth_River	209	Average depth of river	Single
Lanes_Under	210	Number lanes road under	Integer
TypeTerrain_Under	211	Type of terrain under	Byte/String
Access_Under	212	Conditions of access under	Byte/String
Hor_UnderClearance Right	213	Horizontal Underclearance right	Single
Hor_UnderClearance Left	214	Horizontal Underclearance left	Single
Navigation_Control	215	Navigation control	Boolean
Hor_NavClearance	216	Navigation Horizontal clearance	Single
Vert_NavClerance	217	Navigation vertical clearance	Single
LeftCurb_Width	218	Left Curb Width	Single
RightCurb_Width	219	Right Curb Width	Single
Ground_Resistance	220	Estimate of the resistance of the ground	String
Terrain_Under	221	Type of terrain under	Byte/String

- *Defect*

Property		Description	Type
Name	RPIC		
ID	301	Identification code of the defect	Variant

Type	302	Type of the defect (corrosion, spalling, blockage, etc.)	Variant
ElementID	303	Element where the defect is located	Variant
Bridge ID	304	Bridge where the defect is located	Variant
Area	305	Area affected	Single
Unit	306	Unit of area	String
Suggested_Treatment	307	Treatment suggested	Byte/String
Intensity	308	Intensity of the defect	String (Fuzzy)

- *MRI Strategy*

Property		Description	Type
Name	RPIC		
ID	401		Variant
BridgeID	402	Bridge to which the strategy refers	Variant
ElementID	403	Element to which the strategy refers	Variant
MRI_Activity(1)	404	Activity suggested for condition state 1	Variant
MRI_Activity(2)	405	Activity suggested for condition state 2	Variant
MRI_Activity(3)	406	Activity suggested for condition state 3	Variant
MRI_Activity(4)	407	Activity suggested for condition state 4	Variant
MRI_Activity(5)	408	Activity suggested for condition state 5	Variant
Work_Method	409	Suggested Work Method	Variant
Access_Scheme	410	Suggested Access Scheme	Variant

- *Activity (data object)*

Property		Description	Type
Name	RPIC		
ID	501	Activity Identification Code (created by adding TypeCode and MethodCode)	Variant
TypeCode	502	Description of the Type of Activity	Variant
TypeDescription	503	Identification Code of the Type of Activity	String
MethodCode	504	Description of the Method Adopted	Integer
MethodName	505	Identification of the Method Adopted	String
UnitMeasure	506	Unit of Measurement (m / ml / ft / etc)	Byte/String
UnitCost	507	Standard Unitary Cost	Currency
Productity	508	Average Productivity	Single
TP(1)	509	Probability of returning to CS 1	Single
TP(2)	510	Probability of returning to CS 2	Single
TP(3)	511	Probability of returning to CS 3	Single
TP(4)	512	Probability of returning to CS 4	Single
TP(5)	513	Probability of returning to CS 5	Single
EquipmentNeed	514	Fuzzy Characteristic	String
Complexity	515	Fuzzy Characteristic	String
MobilityNeed	516	Fuzzy Characteristic	String
ClosenessNeed	517	Fuzzy Characteristic	String
SetupDuration	518	Fuzzy Characteristic	String
MainDuration	519	Fuzzy Characteristic	String
NoiseProduction	520	Fuzzy Characteristic	String
ContinuityNeed	521	Fuzzy Characteristic	String
Dispersion	522	Fuzzy Characteristic	String

- *Access Scheme (data object)*

Property		Description	Type
Name	RPIC		
ID	601	Equipment Identification Code	Variant
Equipment_Code	602	Access Equipment Used	Variant
Description	603	Description Equipment	String

Manufacturer	604	Identification of the manufacturer	String
General_Type	605	Identification of the type of equipment	Byte/String
Operational_Type	606	Operation Type (under/over)	Byte/String
Access_Type	607	Access Type (vertical/ horizontal/spatial)	Byte/String
Support_Type	608	Type of support (ground / top / suspended)	Byte/String
Horizontal_Reach	609	Maximum horizontal reach	Single
Articulated_Reach	610	Maximum reach from top	Single
Maximum_Width	611	Width of equipment	Single
Total_Weight	612	Total weight in operation	Single
Traction_System	613	Traction system (fixed / tyres / track / unknown)	Byte/String
Productivity Loss	614	Estimate of the Productivity Loss	Single
Length	615	Length equipment (if applicable)	Single
Weight_Capacity	616	Weight capacity (in kg)	Single
Men_Capacity	617	Number men simultaneously working	Integer
Unit size	618	Basic unit of the equipment (vehicle/m3/etc.)	Byte/String
Setup_Cost	619	Cost of setting-up per unit	Currency
Hourly_Cost	620	Hourly cost of operation	Currency
Availability	621	Availability (available/ not available/ rental)	Boolean
Min_UseHeight	622	Minimum height for operation	Single
Min_OptimHeight	623	Lower limit for optimal operation	Single
Max_OptimHeight	624	Upper Limit for optimal operation	Single
Max_UseHeight	625	Maximum height of operation	Single
Noise_Production	626	Estimate of the production of noise	String(Fuzzy)
Time_Continuity	627	Estimates possibility of doing in steps	String(Fuzzy)
Setup_Time	628	Time to set the scheme running	String(Fuzzy)
EasyofOperation	629	Estimates possibility of doing in steps	String(Fuzzy)
Range	630	Estimates of range when using the equipment	String(Fuzzy)
Mobility	631	Estimates the mobility of the equipment	String(Fuzzy)

- *Work Strategy(data object)*

Property		Description	Type
Name	RPIC		
ID	701	Work Strategy ID	Variant
Description	702	Description	String
Adequacy	703	Adequacy to undertake MRI activity	Single
TechAdeq	704	Technical component of adequacy	Single
CostAdeq	705	Cost component of adequacy	Single
EnvAdeq	706	Environmental component of adequacy	Single
FuncAdeq	707	Functional component of adequacy	Single
Loss_Productivity	708	Reduction in productivity	Single
Continuity	709	Estimate of the possibility of uninterrupted work	String (fuzzy)
Noise_Sensibility	710	Estimate of the WS effect on the noise impact	String (fuzzy)
Flow_Reduction	711	Estimate of the impact of the WS in the flow	String(fuzzy)
Daily_Hours	712	Number working hours per day	Single
ActiveHour(n)	713	Indication of activity in hour n	Boolean
Hourly Cost	714	Operational cost	Currency
Setup Cost	715	Cost of setting-up	Currency

- *Project (data object)*

Property		Description	Type
Name	RPIC		
ID	801		Variant
BridgeID	802	Bridge Identification	Variant
StrategyID	803	Strategy Identification	Variant
ElementID	804	Bridge Element Identification	Variant
VI	805	Value Index	Currency
VBU	806	Variation in Bridge Utility	Currency
ECI	807	External Cost of Intervention	Currency

OCI	808	Opportunity Cost of Investment	Currency
VRC	809	Variation in Replacement Cost	Currency
MCI	810	Monetary Cost of Intervention	Currency
Duration	811	Duration Work	Single
Loss_Productivity	812	Loss in productivity	Single
Direct_Cost	813	Direct Cost	Currency
RC_Fixed	814	Fixed part of the related cost	Currency
RC_Variable	815	Variable part of the related cost	Single
IC_Fixed	816	Fixed part of the indirect cost	Currency
IC_Variable	817	Variable part of the indirect cost	Single
AvgSpeed_ Loss(n)	818	Average Speed Loss (main/detour)	Single
AvgTime_Loss(n)	819	Average Time Loss (main/detour)	Single
Extra Consumption	820	Extra Consumption (main/detour)	Single
Work_Method	821	Probable Work Method	Variant
Access_Scheme	822	Probable Access Scheme	Variant
Bridge Value	823	Bridge Value	Currency
UC_Intervention	824	External user cost at intervention	Currency
EC_Intervention	825	External cost of intervention	Currency
EC_Use	826	Environmental costs during use due to deterioration	Currency
UC_Use	827	User cost during use due to deterioration	Currency
UC_Collapse	828	User cost at collapse	Currency

- *Traffic Link (data object)*

Property		Description	Type
Name	RPIC		
ID	901	Identification Code of the Link	Variant
Road_Name	902	Name of Road	String
Road_Type	903	Class of Road (rural/ urban / suburban / interurban)	Integer
Road_Class	904	Type of Road (A road / B road/ local / motorway)	Integer
Road_Duality	905	Number of flow directions (single / dual)	String
Focal_Reference	906	Focal reference (city centre / city /etc.)	String
Flow_Direction	907	Direction of flow in relation to bridge direction (main/ secondary)	String
Orientation	908	Orientation (NW, NE, SE, SW,N,E,W,S)	String
NumberLanes	909	Number lanes in the direction	Integer
Free_Speed	910	Allowable Speed	Single
Width	911	Deck width	Single
ADT	912	Average Daily Traffic	Long Integer
ADTYear	913	Year of reference for ADT	Integer
LGV_Pct	914	Percentage Light Goods Vehicles	Single
HGV_Pct	915	Percentage Heavy Goods Vehicles	Single
PSV_Pct	916	Percentage Passenger Service Vehicles	Single
Length	917	Length of the link	Double
Detour_Length	918	Detour Length	Integer
Detour_Speed	919	Maximum allowable speed detour	Single
Detour_LinkCode	920	Code of the link used as detour	Variant
ExtLoadRoute	921	Part of a Extreme Load Route	Boolean
Function	922	Function (1- Inner Ring Road; 2-Outer Ring Road, 3 – Arterial, 4- Local)	Integer
SchoolBusRoute	923	Part of a school bus route	Boolean
AbnLoadRoute	924	Part of a abnormal load route	Boolean
CriticalRoute	925	Part of critical route	Boolean
EmergencyRoute	926	Part of emergency route	Boolean
DefenseRoute	927	Indicates if part of the Defense network	Boolean
TrunkRoute	928	Indicates if part of the Trunk network	Boolean
AvgNumber Accidents	929	Annual Average Number Accidents	Double
Verge Friction	930	Verge friction	Single
Dif_Speed	931	Difference Speed heavy-light vehicles at zero flow	Single

Sight_Distance	932	Average Sight Distance	Single
Acess_Friction	933	Frequency of lay-bys and intersections in relation to carriageway width	Single
Development_Degree	934	Degree of development	Single
Num_Intesections	935	Number of intersections	Single
Gradient	936	Rise per unit distance	Single
Bendiness	937	Total change in direction per unit distance	Single
Hiliness	938	Total rise and fall per unit distance	Single

- *Policy (data object)*

Property		Description	Type
Name	RPIC		
ID	1001	Identification policy	Variant
Cost_Imp	1002	Importance cost adequacy	Single
Technical_Imp	1003	Importance technical adequacy	Single
Functional_Imp	1004	Importance functional adequacy	Single
Environmental_Imp	1005	Importance environmental adequacy	Single
VBU_Weight	1006	Relative weight given to use and safety benefits	Single
ECI_Weight	1007	Relative weight given to costs of intervention	Single
OCI_Weight	1008	Relative weight given to cost of money	Single
VRC_Weight	1009	Relative weight given to future monetary savings	Single
Value_StandardLife	1010	Value Standard Life	Currency
Value_CO2	1011	Value of reduction of CO2 emission	Currency
Value_SO2	1012	Value of reduction of SO2 emission	Currency
Value_HC	1013	Value of reduction of HC emission	Currency
Value_Particulates	1014	Value of reduction of particulates emission	Currency
Value_NVOC	1015	Value of reduction of n on-metallic organic compounds emissions	Currency
Value_WorkingTime	1016	Value non-working time	Currency
Value_Working Time	1017	Value working time	Currency
ValueTime_Car	1018	Value time average car	Currency
ValueTime_PSV	1018	Value time passenger service vehicle	Currency
ValueTime_HGV	1018	Value time heavy goods vehicle	Currency
ValueTime_LGV	1018	Value time light goods vehicle	Currency
Cost_SeriousAcc	1019	Cost serious accident	Currency
Cost_LightAcc	1020	Cost light accident	Currency
Cost_Fatal	1021	Cost fatal accident	Currency
Prob_SeriousAcc	1019	Probability serious accident	Currency
Prob_LightAcc	1020	Probability light accident	Currency
Prob_Fatal	1021	Probability fatal accident	Currency
Avg_Consumption	1022	Average rate of consumption	Single
Return rate	1023	Return rate on capital	Single
Discount rate	1024	Social discount rate	Single

- *Rule (data object)*

PROPERTY		DESCRIPTION	TYPE
Name	RPIC		
ID	-	Rule identification code	Variant
Domain	-	Domain of the Rule	String
Description	-	Description of the meaning of the rule	String
Importance	-	Importance of the Rule	Single
Fired		Condition	Boolean
Number_Antecedents	-	Number of antecedent conditions in the rule	Byte
Antecedent_Type(n)	-	Type of antecedent n (crisp / fuzzy)	Byte/String
Antecedent_Code(n)	-	Parameter identification code (RPIC) of antecedent n	Long
Antecedent_Fuzzy(n)	-	Fuzzy value antecedent n	Byte/String
Antecedent_Crisp(n)	-	Crisp (defuzzified if adequate) value of antecedent n	Byte
Fuzzy_Vector(n)	-	Vector containing fuzzy number representing	Variant

		antecedent n	
Conclusion_Value	-	Consequence of the rule	Single
Conclusion_Code	-	RPIC consequence of the rule	Long
Observed_Value(n)	-	Observed value antecedent n	Variant
Observed_FuzVal(n)	-	Observed fuzzy value antecedent n	String(fuzzy)
Result	-	Fuzzy result of the rule (using standard linguistic variables)	Byte/String
Crisp_Result	-	Numerical result of the rule (defuzzified if adequate)	Single
Inference_Method	-	Fuzzy inference method to use (0-similarity 1-Mizumoto Standard Sequence 2-Zadeh Min-Max)	Byte
Fuzzy_Type	-	Type of fuzzy membership function to use for subjective arguments (0-standard 1- triangular)	Byte

- *Other data*

The distribution of the main data along the various data objects was shown above. Other intermediary data would also be stored in the various procedural objects and the in the *Status* object.

Considerations about the database structure suggested for ORIGAMI

This appendix discusses briefly the databases proposed for implementation in ORIGAMI. Pointing to the difficulty in representing all bridge data in the table format of relational databases, Itoh et al. [1997] defend the idea of using object-oriented databases to store the inspection and inventory data. While the author considers this a good trend for the future, there are reservations about the current ability of some users in dealing with this type of databases at the present time. Therefore, for practical reasons, it was decided that the modules developed would use a relational database that would be more familiar to users. It is important to highlight that with this solution the databases could be manipulated directly using a proprietary specialised software – Microsoft Access – giving more freedom to the user. It is also possible to use multimedia information associated with the traditional tabular information.

- *Structure*

It was considered necessary to establish nine databases to support the initial version of ORIGAMI proposed in this thesis, as seen in figure 1. The databases structure proposed took into consideration the fact that, according to the framework for change established in chapter 7, the databases would probably be stored in different places depending on their nature and characteristics. As suggested in the figure, four databases are expected to stay under the control of local authorities: Bridge Inventory, MRI Actions, Access Equipment and Inspection Data. The Access Equipment database could eventually become an on-line virtual database that would collect data over the Internet directly from suppliers. The central database is designed to contain data about all the bridges in the network and would be maintained by a central planning or financing authority.

The database containing data about the MRI projects could also stay at the central authority but, most likely, it would be delegated to the local authorities. It is expected that the traffic database will be maintained by the traffic authorities while the rules and the support databases would probably be stored together with the ORIGAMI system.

When dealing with databases it is always necessary to consider the question of size. A conservative approach was adopted and care was taken to avoid using large text fields, because the number of records involved in bridge management is usually high. Analysing the structure of the databases (described in appendix IV), it can be seen that the majority of them would not generate problems. They could reach considerable sizes if the number of structures to consider was large (more than 50.000) but would still be reasonably easy to work with, specially considering that they could be distributed between different authorities. The question of size is therefore not considered as relevant in the present case. Each of the databases is briefly discussed below

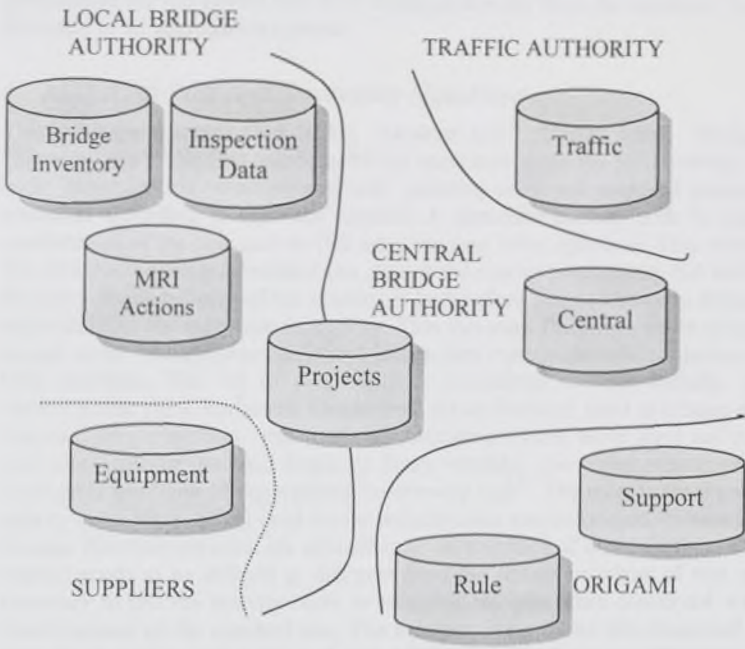

Figure V.1 – Representation of the Database Structure

- *Bridge Inventory Database*

This database is divided in various tables that contain data about the bridge as a whole and its constituent elements. A large amount of data on the general and functional characteristics of each bridge is stored in the Bridge Info table. The structure of this table followed in general terms the one used in PONTIS database [Golabi et al., 1993] and the codes adopted were usually adapted from the U.S. Coding Guide [FHWA, 1988] and the QUADRO manual [DOT, 1989]. Each bridge is identified by a unique code. Each element inside a bridge has also a unique code but to locate a particular element it is necessary to give both the element as well as the Bridge ID. The information about the elements was organised in different tables according to the element type (or "family"). This was necessary because different information is necessary to describe elements of different shapes and functions such as a bearing and an expansion joint. Many of the 116 elements used in PONTIS are however similar and could be classified as being of the same family.

- *Inspection Data Database*

This database contains data about the problems diagnosed by the bridge inspectors and how they were translated into Condition States. It contains three tables. The first one is responsible for storing data about the inspections themselves, including date, type, code of the inspector and special observations annotated. The two other tables contain the actual inspection results. The first one stores data by defect, cross-referencing against the Element and Defect databases. Information about the gravity of the defect is also provided, following the procedure used in the system for bridge inspection devised in Porto Alegre [Klein et al., 1993], which established notes based on a numerical scale varying from 0-5, with 5 meaning a serious defect and 0 meaning no defect. This information could be aggregated to calculate the condition of the element as a whole. The second table stores the results of this aggregation, using the PONTIS probabilistic notation that allows the classification of portions of the element in different condition states. A special field is used to differentiate the CS grades that were obtained directly from the inspector from the ones that were the result of an aggregation exercise.

- *MRI Activities and Strategies Database*

This database contains four tables: "General Info", "Fuzzy Info", "Probabilistic Effects" and "Strategy Info". The first one contains the basic data about the MRI activity, such as identification code, denomination, measurement unit, standard costs and standard productivity. Activities are classified according to type and method. A particular activity code would therefore refer to a combination of the two such as (fill crack)/(epoxy resin injection). This scheme is justified by the fact that the variation in method can change the cost or productivity but will not normally change the fuzzy characteristics of the activity. It is therefore just necessary to define the matrix of fuzzy characteristics for each type of activity. This increases flexibility while saving storage space. The second table, "Fuzzy Characteristics", stores data representing the subjective characteristics of the MRI activities. The list of characteristics considered relevant include: complexity, mobility, vertical access need, horizontal access need, set-up duration, need of closure during set-up, need for closure during execution, time continuity, equipment need, noise level and proximity required. To save space each of the main linguistic fuzzy variables was coded numerically with 0 representing "extremely low" and 10 representing "extremely high". The records are organised according to the activity type, but a special field for the activity code was introduced. Normally it will be set to zero because the characteristics are applicable to all activities of a certain type. If however a particular method needs to be defined as different from the rest of activities of that specific type it is just necessary to put the activity code in here that the procedure concerned will take the particular record instead of the standard one. The two remaining tables are concerned with storing the data from the transition probabilities of each MRI activity and the characteristics of the MRI strategies (combination of activities to treat a single element) being considered.

- *Traffic Information Database*

This database contains data about the volume and type of traffic in each bridge. It will also contain information about the traffic flow characteristics of the streets and roads in the vicinity of the bridge, necessary for the determination of detour routes and the estimation of the impact of the detoured vehicles in these routes. It is advocated that the data should be organised by links in a way that is compliant with the geographical representation of the network used in the GIS component.

- *Access Equipment Database*

This database is dedicated specifically to store data necessary to undertake the selection of the access method. The database will be composed by two tables containing data about the general and the fuzzy characteristics of each type of access equipment. A flag field shows which ones are available to be considered in the analysis. The fuzzy info table works in a similar fashion the to the homonymous one in the MRI Activities and Strategies database.

- *Project Database*

The Project database contains the list of projects and the main information resulting from the appraisal exercise. This information is used to adapt the Value Index when performing work packaging (Theoretically it would be possible to activate appraisal to retrieve this information dynamically but it was considered that having this information already stored could save processing time). The data is stored according to the project code and this could in time be linked to planning files produced in project management software to allow a seamless verification of the development of the project. To differentiate between the various types of Combo projects they were classified in Bridge, Zone and Thematic.

• *Rule Database*

The rule database provides the raw data for the undertaking of soft reasoning. A very flexible structure is proposed to allow the continuos updating of the rule base. Each rule is identified by a unique number and can have up to three arguments, as discussed in chapter 8. Users can introduce more rules whenever desired.

• *Support Database*

The support database contains all the miscellaneous data necessary to support the analysis, such as current policies, weights, code references, fuzzy membership functions, etc. Data about the various work methods will also be maintained here.

• *Central Database*

The central database contains a summary of the results of the analysis. It contains two tables. The first one is organised to reproduce the data used in PONTIS in a way that would allow some compatibility. It includes the *Bridge.ID* field and the percentages of elements in each condition state. The second lists the projects under consideration and their value index. The prioritisation of the activities over the network is done using this data, with recurrence to the more detailed information contained in the other tables when necessary. After the list of approved projects is produced it goes back to the local authorities to allow programming, as described earlier. This appendix describes the various databases proposed to support the ORIGAMI system. Special attention is given to the codes used to translate the data stored into useful information.

• *MRI Activities Database*

The way the "Fuzzy Characteristics" table was structured means that it is necessary to change the table design using a database management software (i.e. Microsoft Access) to include new fuzzy characteristics. An alternative design that would overcome this problem was tested. It implied the definition of a unique fuzzy code to represent each fuzzy characteristic. While effective this representation would reduce the clarity of the data storage. Therefore, considering that the need to include a new fuzzy characteristic would probably not be frequent, it was decided that it is preferable to have a more easily understandable table structure instead of a more flexible one.

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Appendix VI

Considerations about Rules used in the Approximate Reasoning Procedures

This appendix discusses how rules will be used, stored and processed in ORIGAMI and presents the initial set of rules proposed for the author to help select work strategies and access schemes. These were used in the validation and verification tests carried out in chapter 11.

- *Rule Storage*

The rule databases is discussed in Appendix V but some aspects related to it must be highlighted. The first is that fuzzy values are usually translated into a numerical scale for storage. "High" is for example associated with the code 8 and a rule would therefore be represented by a numerical vector. Another aspect is that each rule is assumed to have a maximum of three arguments. This limitation could be overcome by changing the structure of the database. The author investigated one structure that would get rid of this limitation altogether but this would lead to more complex storage and retrieval mechanisms. Since all the rules created abided to the limitation discussed above, this was not considered necessary.

- *Rule Interpretation*

The *Parameter_Interpreter* is an internal method of the *Rule* object. Its function is to interpret the numerical codes contained in a stored rule record. This means that, receiving as an argument "CodeArg1" or "CodeArg2" it uses an internal list of associations to discover which parameter should be evaluated. The parameters can be fuzzy, such as *Activity(Continuity)*, or crisp, such as *Bridge(Height)*. Based on this listing it retrieves and returns the current value of the parameter. Appendix V presents a list of the objects suggested with their main properties and the respective identification codes.

- *Rule Processing*

The rule processing is commonly done by using the min-max operator to determine the firing strength. It is interesting to remember that if a rule tries to retrieve a property value that is irrelevant in the current situation (fact especially common with the *Element* data object that can represent various types of element with different characteristics), the property value that is given to be compared with the stored rule is a null vector. This implies that the min-max operator will return a firing strength of zero and the rule will not have any effect. This adequately simulates the fact that in real life the rule would not have been considered by an expert.

- *Rule Listings*

The next items present the listings of rules suggested for the fuzzy selection procedures. This is just a sample of the possible rules that could be used. They nonetheless are already sufficient to give ORIGAMI a reasonable reasoning power, as demonstrated in chapter 11. As discussed in the body of the thesis more rules could easily be incorporated by the user if desired. The author would like to stress that many of the properties used in the rules are in fact codified, such as the *Equipment(ID)* or *Span(UseUnder)*. However, the linguistic interpretation of the codes will be used in the listings for clarity. Another thing to highlight is that many properties are not originally present in the databases but are in fact derived by the various objects from data existing in the database. The rules were develop by the author from the examination of expert reasoning and the evaluation of technical aspects to help estimate what would be the access scheme and the work strategy that would be preferred in a certain situation.

- *Rules for Access Scheme Selection*

<u>Domain AS:TechAdeq</u>
Rule AST1: Height Adequacy Check

Rule AST2: *If Span(Vert_UnderClearance) < 3 AND Span(UseUnder) = "Road" AND Access Scheme(ID) = "Suspended Scaffold" THEN Access Scheme(TechAdequacy) = "Nil"*

Rule AST3: *If Element(family)="column" AND Access Scheme(AccessType) = "vertical" THEN Access Scheme(TechAdequacy) = "high"*

Rule AST4: *If Activity(EquipmentNeed)="High" AND AccessScheme(EasyofOperation) = "Low" THEN Access Scheme(TechAdequacy) = "Low"*

Rule AST5: *If Span(GroundResistance) = "Low" AND Access Scheme(TotalWeight) = "High" And Access Scheme(SupportType) = "Ground" THEN Access Scheme(TechAdequacy) = "Low"*

Rule AST6: *If Span(UseUnder) = "River" AND Access Scheme(SupportType) = "Ground" THEN Access Scheme(TechAdequacy) = "Nil"*

Rule AST7: *If Span(AccessUnder) = "Bad" AND Access Scheme(SupportType) = "Ground" THEN Access Scheme(TechAdequacy) = "Low"*

Rule AST8: *If Activity(Complexity) = "High" AND Access Scheme(EasyofOperation) = "Low" THEN Access Scheme(TechAdequacy) = "Low"*

Rule AST9-A: *If Activity(MainDuration) = "Low" AND Access Scheme(SetupTime) = "High" THEN Access Scheme(TechAdequacy) = "Low"*

Rule AST9-B: *If Activity(MainDuration) = "Low" AND Access Scheme(SetupTime) = "Low" THEN Access Scheme(TechAdequacy) = "Low"*

Rule AST10-A: *If Span(TerrainUnder) = "Rough" AND Access Scheme(TractionSystem) = "Tyre" THEN Access Scheme(TechAdequacy) = "Very Low"*

Rule AST10-B: *If Span(TerrainUnder) = "Road" AND Access Scheme(TractionSystem) = "Track" THEN Access Scheme(TechAdequacy) = "Slightly Low"*

Rule AST11-A: *If Activity(Dispersion) = "High" AND Access Scheme(Range) = Low AND Access Scheme(Mobility) = "Low" THEN Access Scheme(TechAdequacy) = "Low"*

Rule AST11-B: *If Activity(Dispersion) = "High" AND Access Scheme(Range) = Low AND Access Scheme(Mobility) = "High" THEN Access Scheme(TechAdequacy) = "Medium"*

Rule AST11-C: *If Activity(Dispersion) = "High" AND Access Scheme(Range) = "High" THEN Access Scheme(TechAdequacy) = "High"*

Rule AST12: *If Activity(MobilityNeed) = "High" AND Access Scheme(Mobility) = "Low" Then Access Scheme(TechAdequacy) = "Low"*

<u>Domain AS:CostAdeq</u>

Rule ASC1-A: *If Access Scheme(SetupCost) = "High" THEN Access Scheme(CostAdequacy) = "Low"*

Rule ASC1-B: *If Access Scheme(SetupCost) = "Medium" THEN Access Scheme(CostAdequacy) = "Medium"*

Rule ASC1-C: *If Access Scheme(SetupCost) = "Low" THEN Access Scheme(CostAdequacy) = "High"*

Rule ASC2-A: *If Access Scheme(HourlyCost) = "High" AND Activity(Duration) = "High" THEN Access Scheme(CostAdequacy) = "Low"*

Rule ASC2-B: *If Access Scheme(HourlyCost) = "Medium" AND Activity(Duration) = "High" THEN Access Scheme(CostAdequacy) = "Slightly Low"*

Rule ASC2-C: *If Access Scheme(HourlyCost) = "Low" AND Activity(Duration) = "High" THEN Access Scheme(CostAdequacy) = "Fairly High"*

<u>Domain AS:FuncAdeq</u>

Rule ASG1: *If Link(ADT) = "High" AND Element(FreeLateralSpace) = "Low" AND Access Scheme(SupportType) = "Ground" THEN Access Scheme(FuncAdequacy) = "Low"*

Rule ASG2-A: *If Link(ADT) = "High" AND AccessScheme(SupportType) = "On" AND Link(UseUnder) ≠ "Road" THEN Access Scheme(FuncAdequacy) = "Very Low"*

Rule ASG2-B: *If Link(ADT) = "High" AND AccessScheme(SupportType) = "Suspended" AND Link(UseUnder) ≠ "Road" THEN Access Scheme(FuncAdequacy) = "Slightly Low"*

Rule ASG3: *If Link(Size) = "Single" AND Access Scheme(SupportType) = "On" THEN Access Scheme(FuncAdequacy) = "Fairly Low"*

<u>Domain AS:EnvAdeq</u>
Rule ASE1-A: *If Bridge(NoiseSensibility) = "High" AND Access Scheme(Noise Production) = "High" THEN Access Scheme(EnvAdequacy) = "Low"*

Rule ASE1-B: *If Bridge(NoiseSensibility) = "Low" AND Access Scheme(Noise Production) = "High" THEN Access Scheme(EnvAdequacy) = "Fairly High"*

- *Rules for Work Strategy Selection*

<u>Domain WS:TechAdeq</u>
Rule WST1: *If Activity(ContinuityNeed) = "High" AND WorkStrategy(Continuity) = "Low" THEN WorkStrategy(TechAdequacy) = "Very Low"*

Rule WST2: *If Activity(ContinuityNeed) = "High" AND WorkStrategy(Continuity) = "High" THEN WorkStrategy(TechAdequacy) = "Very High"*

Rule WST3: *If Activity(ContinuityNeed) = "Medium" AND WorkStrategy(Continuity) = "High" THEN WorkStrategy(TechAdequacy) = "Medium"*

Rule WST4: *If Activity(ContinuityNeed) = "Medium" AND WorkStrategy(Continuity) = "Medium" THEN WorkStrategy(TechAdequacy) = "Medium"*

Rule WST5: *If Activity(ContinuityNeed) = "Medium" AND WorkStrategy(Continuity) = "Low" THEN WorkStrategy(TechAdequacy) = "Fairly Low"*

Rule WST6: *If Bridge(DirectionTraffic) = "One-Way" AND WorkStrategy(ID) = "Shuttle" THEN WorkStrategy(TechAdequacy) = "Nil"*

<u>Domain WS:EnvAdeq</u>

Rule WSE1: *If Bridge(NoiseSensibility) = "High" AND Activity(NoiseEmission) = "High" AND WorkStrategy(NoiseSensibility) = "High" THEN WorkStrategy(NoiseAdequacy) = "Very Low"*

Rule WSE2: *If Bridge(NoiseSensibility) = "High" AND Activity(NoiseEmission) = "High" AND WorkStrategy(NoiseSensibility) = "Low" THEN WorkStrategy(NoiseAdequacy) = "Slitghly High"*

Rule WSE3: *If Bridge(NoiseSensibility) = "High" AND Activity(NoiseEmission) = "Medium" AND WorkStrategy(NoiseSensibility) = "High" THEN WorkStrategy(NoiseAdequacy) = "Slightly Low"*

Rule WSE4: *If Bridge(NoiseSensibility) = "High" AND Activity(NoiseEmission) = "Medium" AND WorkStrategy(NoiseSensibility) = "Medium" THEN WorkStrategy(NoiseAdequacy) = "Medium"*

Rule WSE5: *If Bridge(NoiseSensibility) = "High" AND Activity(NoiseEmission) = "Medium" AND WorkStrategy(NoiseSensibility) = "Medium" THEN WorkStrategy(NoiseAdequacy) = "Medium"*

Rule WSE6: *If Bridge(NoiseSensibility) = "High" AND Activity(NoiseEmission) = "Medium" AND WorkStrategy(NoiseSensibility) = "Medium" THEN WorkStrategy(NoiseAdequacy) = "Medium"*

<u>Domain WS:FuncAdeq</u>

Rule WSU1: *If Link(ADT) = "High" AND WorkStrategy(FlowReduction) = "High" THEN WorkStrategy(FuncAdequacy) = "Low"*

Rule WSU2: *If Link(ADT) = "Low" AND WorkStrategy(FlowReduction) = "High" THEN WorkStrategy(FuncAdequacy) = "Medium"*

Rule WSU3: *If Link(ADT) = "Low" AND WorkStrategy(FlowReduction) = "Medium" THEN WorkStrategy(FuncAdequacy) = "Medium"*

Rule WSU4: *If Link(DiversionLenght) = "High" AND WorkStrategy(FlowReduction) = "High" THEN WorkStrategy(FuncAdequacy) = "Low"*

Rule WSU5: *If Link(DiversionLenght) = "Low" AND WorkStrategy(FlowReduction) = "High" THEN WorkStrategy(FuncAdequacy) = "Medium"*

Rule WSU6: *If Link(DiversionLenght) = "Low" AND WorkStrategy(FlowReduction) = "Low" THEN WorkStrategy(FuncAdequacy) = "High"*

<u>Domain WS:CostAdeq</u>

Rule WSC1: *If WorkStrategy(Cost) = "High" THEN WorkStrategy(CostAdequacy) = "Low"*

Rule WSC2: *If WorkStrategy(Cost) = "Medium" THEN WorkStrategy(CostAdequacy) = "Medium"*

Rule WSC3: *If WorkStrategy(Cost) = "Low" THEN WorkStrategy(CostAdequacy) = "High"*

Appendix VII

Considerations about the models used to subsidise the appraisal sub-system of ORIGAMI

This appendix contains some information about the models used to support the appraisal sub-system of the initial version of ORIGAMI. The various models are briefly described explaining how they would function. Appendix VIII shows how they could be used collectively to appraise the best MRI strategy for a particular bridge.

- *Traffic Assignment*

One of the most important consequences of the adoption of the novel appraisal model proposed by the author in this thesis will be the need for incorporating in the "virtual" structure of an advanced system a traffic assignment model, as discussed in chapter 9.

As verified in chapter 11, the adoption of different work strategies will strongly affect the impacts of the intervention. It is necessary to define the probable strategy and examine the consequences of its adoption in the traffic flow since in certain cases this can be vital in determining the Value Index of a certain MRI strategy. Current systems do not have any provision for such calculations and therefore their results can be seen as lacking in precision

To determine the impact of different work strategies a traffic assignment model will be used. This model will distribute the ADT into hourly traffics, determine the speed-flow relationships based on the characteristics of the structure and of the traffic flow and analyse the effect of the intervention in the main route and the detour.

The traffic assignment model to be used in ORIGAMI will be based on the one used on the QUADRO software but it will be adapted to increase flexibility and facilitate data inputs.

The working of the assignment model is based on the establishment of queue equilibrium between the main route and the detour. When the detour route is formed by more than one link, however, it is necessary to homogenise the information to feed into the model. For example, figure VII-1 shows a model network where the detour from B2 to C2 is formed by three segments of different roads with distinct characteristics and capacity. It is necessary to combine the properties of links I, II and III that form the detour in the southbound direction to create an adequate "virtual" detour route to be used in the traffic assignment calculations.

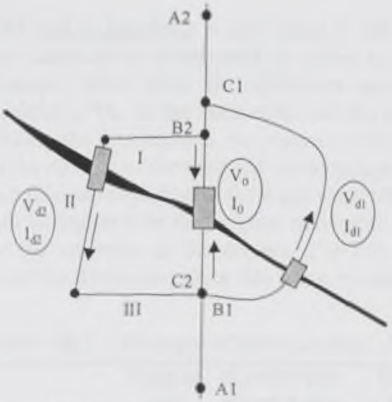

Figure VII-1 – Representation of a model network.

To determine the values for the virtual link it would be possible to use a procedure similar to that used in the QDIV program [DOT, 1987] developed to support the QUADRO software. The author considers that this procedure would be adequate for the initial version of ORIGAMI but more sophisticated ones using the GIS capabilities can be envisioned for later versions.

The assignment model will establish the number of vehicles detoured and calculate the reduction in speed caused by the intervention in the main route and the detour, as exemplified in the tables presented in Appendix VIII. This information is then utilised to calculate the time losses, the increase in travel length and the changes in fuel consumption. These are the parameters necessary to determine the user and environmental (external) costs during interventions, as discussed below.

- *User Costs during Intervention*

As discussed in chapter 5, the user costs will depend on three basic factors:

- Delays
- VOC
- Accidents

The delays are the result of time losses incurred in congested traffic or in the use of a detour. The traffic assignment model provides the necessary information about speed reductions and vehicle detoured to allow the estimation of these time losses. If necessary simplified relationships such as the one suggested by Bristow and Ling [1989] could be used to make a rough estimate of the delay. Having defined the time losses the values of time per vehicle type defined in Appendix III can be used to estimate the delay cost.

The VOC can be calculated either using the standard formulae discussed in QUADRO or by taking into consideration the results of the traffic assignment model, as follows:

$$VOC= (\text{extra consumption}) * \text{fuel price} + (\text{extra km}) * (\text{Running Cost}_{\text{not-fuel}}/\text{km}) \quad \text{(Eq. VII-1)}$$

The first parcel of the VOC is calculated using the information about the extra consumption and the fuel retail prices. The second parcel of the VOC is linked to deterioration and functional depreciation and is calculated by multiplying the extra travel length by a cost rate per extra kilometre travelled established by the user to represent the deterioration, maintenance and depreciation costs. According to the AA [1998], this rate can be estimated at around 9 pence/km.

The cost of accidents is calculated in ORIGAMI using the accident rates suggested in QUADRO. An intervention is assumed to cause an increase in the accident rates. Table VII.1 presents an example taken from the validation exercise undertaken in chapter 11. The Probability of an accident (PIA) in the main route and the detour are established at 0.3 and 0.25 ($x10^{-6}$) respectively. During the intervention, the chances of an accident are elevated to 1×10^{-6} because of the presence of the closure of the road and the stoppage needed. An off-peak service was however being running and this rate is just valid for when the traffic is on. When the site is off the rate is reduced but it will still be higher than the original one because of the presence of the works and the consequent effect on the attention of the drivers. The risk on the detour would be higher if significant diversion occurred. However, since this is not necessary there will be no increase.

Table VII.1 – Example of determination of the VOC.

	Total no. veh.	Number veh affected site	PIA ($x 10^{-6}$)	PIA* Site On ($x 10^{-6}$)	PIA * Site Off ($x 10^{-6}$)	Daily Total Risk Accidents
Main before	20000	-	0.3	-	-	0.018
Detour before	6677	-	0.25	-	-	0.007511625
Main during	20000	14214	0.3	1	0.35	0.01902391
Detour during	6677	0	0.25	0.3	0.25	0.007511625

To determine the monetary value the accidents the following equation was used:

$$\Delta \text{ Cacc (int.)} = \text{Cacc(main, int.)} + \text{Cacc(detour, int)} - \text{Cacc(main, before)} - \text{Cacc(main, before)} \quad \text{(Eq. VII-2)}$$

Each of these is a result of the risk of accidents versus the average cost of accidents. The average accident cost is calculated by multiplying the probabilities of fatal, serious and slight accidents against the average estimates of the cost incurred for each of these types of accident. These can be extracted from national surveys published by the government or can be imposed by the sure.

- *Atmospheric Emissions (Environmental Costs during Intervention)*

As explained in the main body of the thesis, several environmental impacts can occur during a MRI intervention including noise, disruption of habitats and visual pollution. However, since MRI interventions are usually short termed, the significance of some of these impacts is usually small. The most significant damage is the additional atmospheric pollution and the author decided to focus on this issue.

The atmospheric emissions model is based on the valuation, in monetary terms, of the environmental cost of additional atmospheric emissions caused by the extra consumption of fuel. The consumption raises because as a result of lower speeds and increased travel distances (for vehicles detoured). To determine the extra consumption it is necessary to establish a relationship between speed and consumption, as indicated in figure VII-2.

This relationship was calculated based on data from the Friend of the Earth [1998]. It is supported also by data in the Bosch Automotive Handbook [Bosch, 1995]. According to it, during starting, warming up or accelerating periods the excess air factor (λ), which in normal speed is around 1.3 (lean mixture), goes down to 0.5 (rich mixture), meaning that the consumption rises considerably and that the emission increase because the burning of the fuel is less efficient. The difference can be significant, as seen in table VII-2.

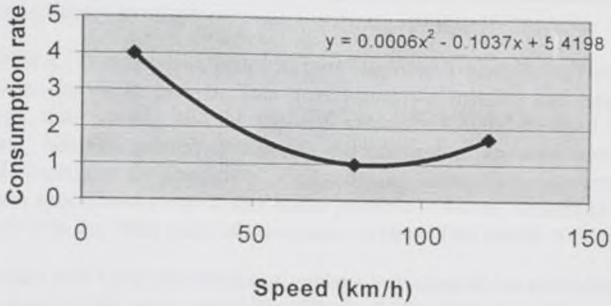

Figure VII-2- Speed–consumption relationship.

Table VII-2 – Emissions of a diesel engine submitted to different acceleration levels.

Emission	Unit	Motor Regime	
		IDLE	MAXIMUM
Nox	ppm	50 – 250	600 – 2500
Hydrocarbons	ppm	50 – 500	150
CO	ppm	100 – 450	350 – 2000
CO_2	% Vol	Up to 3.5	12 – 16
Water Vapour	% Vol	2 – 4	Up to 11%
Soot	mg/m^3	Around 20	Around 200

Based on a relationship such as the above and knowing the length of detour, the additional consumption can be calculated. Using the data about the average emissions of motors provided by Volkswagen [1995] and the Bosch Automotive Handbook [1995], summarised in table III-2 (see Appendix III), the amount of emissions can be estimated. It is important to highlight that the values on table III-2 include the emissions during the whole process chain, from production to consumption. Users may desire to adjust the values to reflect the fact that environmental taxes may already be embedded on the taxes on the production and retail of fuel. The cost of the atmospheric emissions is then calculated by associating a monetary value to the various components of the emissions, as seen in Appendix III.

The author would like to stress that there are certain types of permanent environmental damage apart from atmospheric pollution that could occur in certain special circumstances, such as the destruction of habitats, the disturbance or death of rare fauna/flora specimens and the pollution of sensitivity areas. These impacts could hypothetically have a significant monetary expression, especially in large or long-term jobs. If these types of environmental consequences can be assessed and related to the undertaking of the MRI work, they should be incorporated in the calculations. It will be necessary nonetheless to develop suitable tools to assess their probability of occurrence and monetary significance. Since these tools are not yet available and these impacts are not commonplace they were not considered in this thesis. But the philosophy behind the appraisal model proposed by the author justifies the undertaking of more studies in this area and their incorporation in the future.

- *Noise Impact*

Despite not being included in the environmental cost of intervention, in some circumstances the assessment of the noise impact is necessary. This will occur for example when improvement strategies change the traffic flow in a significant way. A more common use would be to help select the work strategy to adopt.

The FHWA [1995a] recommends its own Highway Traffic Noise Prediction Model, STAMINA 2.0 to predict the noise impact. This model uses the number and type of vehicles on the planned roadway, their speeds, and the physical characteristics of the road (e.g., curves, hills, depressed, elevated, between others). Following the concept of an open architecture, ABMSs developers should investigate the possibility of establishing connections between the main core of the systems and such specialised tools. If this is not possible however, simplified models need to be developed and linked to the other parts of the system. A simplified model is discussed below.

The model will have two functions: make a valuation of the noise impact or, more commonly, just assess roughly the noise sensibility. The basis for both calculations will be the number of people affected

Briefly, the sequence of operations to calculate noise sensibility would include:

1) Determination of intensity of noise source;

2) Determination of noise dispersion;

3) Determination of noise impact

4) Valuation of noise impact

<u>Intensity of noise source</u>

The determination of the noise source intensity is done by analysing and combining the noise emission of vehicles. A standard value of 93 dB can be assumed to the traffic noise at source [FHWA, 1995] or a calculation can be made to estimate the value depending on the traffic characteristics of the link.

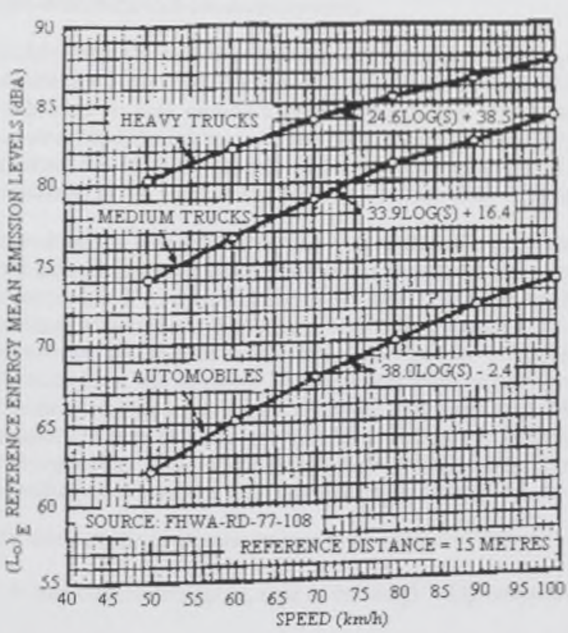

Figure VII-3 – Noise levels for various vehicle types.

If a calculation is performed, it should take into consideration the hourly ADT, the mix of vehicles in the link and the emission of each type of vehicle. Figure VII-3 indicates the noise levels for various types of vehicle at varying speeds. The addition could be made following the simplified guidelines provided by the FHWA that state that if the dBA difference between sources is less than 1 dBA, 3 dBA should be summed to the highest source. If the difference is between 2-3 dBA, 2 dBA should be added. If the difference is between 4 and 9 dBA, 1 dBA should be added to the highest source. Otherwise, just the highest source should be considered.

Noise Dispersion

Assuming ideal conditions, the sound pressure in a far free field decreases inversely with distance [Beracek, 1960]. Considering a non-directional noise source of 93 dBA at 15 m from the structure, the sound pressure level (SPL) at a distance x (in metres) would therefore be:

$$SPL(x)=93 - 20 \text{ Log } (x/15) \qquad \text{(Eq. VII-3)}$$

With this formula, it is possible to calculate the approximate sound pressure for each building in the vicinity of the bridge. No attenuation will be considered in the initial form of the model. Attenuation and directionality considerations can be added if desired but this would require additional information and the benefits of increased precision would be few.

Noise Impact

Sophisticated models for noise prediction based on the use of GIS are available [Nielsen, 1996] that take into account reflection and attenuation [Jones, 1996]. This demonstrates the usefulness of this tool and the great opportunities opened by its introduction in the advanced systems. Considering the initial resistance from user to great increases data collection and the need for specific knowledge to run the most sophisticated models, a simplified model will be proposed for the initial version of ORIGAMI. When the philosophy proposed in this thesis has been effectively incorporated into bridge management more precise models can be easily introduced because of the open architecture of advanced systems.

To determine the buildings that should be analysed the simplified model will also make use of the capabilities of the GIS component The MapInfo software allows the use of a "buffer" function that establishes an area around a certain object. The idea is to use this function to draw isometric curves around the bridge to define areas where the noise originating from the structure could be a problem. Based on the guidelines discussed in Appendix III sound levels below 55 dBA noise are considered as not significant. This will limit the sizes of the areas to consider.

To reduce the impacts in various types of buildings to the same basis reference levels were established based on the acceptable noise thresholds discussed in Appendix III. For residences, the reference level was established at 76 dBA. Considering that a variation of 10 dBA implies a doubling of loudness, the impact at 86 dBA would be 2 times the impact at reference level. Conversely, the impact at 66 dBA would be just 0.5 times the impact at reference level. The reference level for sensitive buildings (churches, schools) was established at 67 dBA while the reference level for special areas (Hospitals, etc.) was established at 55 dBA. It was also considered necessary to take into account that different types of buildings have different rates of occupancy. Studying values of population equivalencies proposed by the Health and Safety Executive [1988] the author developed the scale summarised in table VII-3.

With this data the total noise impact is calculated as folows:

NI = EqLoudnessImpact (x, type of building) * EqNumberPeople (type of buildnig) (Eq. VII-4)

Table VII-3- Population Equivalencies.

Size	Housing	Housing Blocks	Leisure	Commercial	Hospital, etc.
Small	2 people	10 Small Houses	15 people	25 people	100 people
Large	5 people	30 Small Houses	50 people	75 people	300 people

During the running of the model the GIS component checks each of the objects contained inside the buffer zone, determines the sound level as described in equation VII-5, checks the type of building and then calculates the loudness impact. The noise impact on each building inside the buffer zone could then be roughly estimated. The total impact is calculated by adding the values for each building.

Noise Impact Valuation

Usually it will be necessary to estimate just the noise sensibility. However, in some cases a monetary value might be necessary. To determine the monetary expression of the noise impact the simplified model makes use of the data that an acceptable cost for noise abatement measures would be £20,000. Assuming a 10 dBA variation is a significant abatement, this value will be associated, for normal house, with the reduction from 86 to 76 dBA. Dividing the monetary value by the sum of the loudness impacts for each 1 dBA reduction in this interval, an average rate of value per equivalent loudness reduction can be calculated. Using this rate, the value for other intervals of reductions can then be established.

- *Related Cost*

The initial related cost model to be used in ORIGAMI considers that the RC is dependent on three factors, as described in chapter 9:

- Set-Up Costs
- Material Haulage Costs
- Access Costs

The set-up costs should preferably be calculated using a composition. They could also be estimated based on information obtained from performing the same activity on similar bridges. While these facilities are not implemented, they will just reflect standard parameters given by the user.

The material haulage costs will be calculated using a standard transportation unit cost given by the user and the distance from the provision/destination site. The user could also give the later but the idea is to use the GIS component to calculate it. In any case, it is first necessary to apply approximate reasoning to decide if material haulage is "probable". The haulage costs are usually not very important, unless the activity involves great intakes or removals of material and the bridge is located in a remote area.

The access costs include the cost of the access equipment and the additional costs arising from the loss of productivity associated with difficult work conditions in elements of difficult access. In relation to the first element, the costs will depend on the type of the equipment and the duration of the work. The user should provide the hourly cost of operation during the registration of each new type of access equipment. The use of certain types of access equipment will have effects on the productivity. Estimates for the loss in productivity that would occur were obtained by the author from the experts during the interviews and are presented in Appendix I.

- *Indirect Cost*

The author considers that the traffic management cost should be estimated based on previous experiences. An estimation function might be developed based on parameters such as the flow of vehicles, type and length of bridge and the duration of the intervention. Since data about this is available and this was not the focus of this research, the author did not try to develop such a function.

- *Bridge Value*

Bridge Value is calculated as the result of the sum of the Asset Value, the Functional Value, the historic Value and the Strategic Value. The model proposed is an adequate representation of the way experts reason. It explains how considerations about safety can lead to the attachment of high "value" to undertaken of actions in certain bridges that could not be justified if just the asset value were considered as forming the Value at Risk. It also indicates why the work in bridges that become redundant or obsolete is given much less importance (rapid reduction in functional and strategic value) unless there is a strong risk to users or passers-by (increase in the user cost at normal operation).

The components of the model are calculated as follows:

Asset Value: Sum of the replacement cost of the various elements.

$AV = \Sigma_i [R(Ei)^* Q(Ei)]$

Functional Value:

Is calculated by adding the daily ECI (external cost of intervention – user and environmental) generated by a total closure work strategy year by year during the time interval determined by the planning horizon chosen. Each year the daily ECI is adjusted to account for the growth in traffic volume.

$FV = \Sigma_n [ECI(n) * 365]$

If the ECI is differentiated according to the day off the week the calculation should be adjusted to take this into account.

Strategic Value

As discussed in Appendix III, the strategic value depends upon the strategic relevance. An experiment was conducted during the interviews with the experts to determine which factors should be part of such an index. The experts were asked to classify 15 bridges according to their strategic importance using a relative scale from 0 (not important) to 100 (extremely important in strategic terms). A series of variables relating to the unique characteristics of each bridge or to its position relative to focal points such as the city centre and the airport was created to check if it was possible to develop a model that would simulate the behaviour of the experts.

It is considered that the best possible way to try to estimate the strategic importance would be by analysing the relative position of the bridge in the network in relation to the focal points and use some subjective set of weights to calculate the strategic importance. The GIS component discussed earlier would be a suitable tool to assess the distance of the bridge to certain focal point such as hospital and schools. The distance measured could be taken as an indication of the strategic importance of the bridge to that facility. A non-linear relationship could be established, so the importance would decay more rapidly with the distance. The factors to consider could include focal points such as police stations, schools, universities, hospitals, churches; the city centre, important tourist's attractions and transport modes exchange facilities, i.e. airports, trains and inter-city buses stations, harbours, etc.

- *Risk Function*

To help establish a risk function questions were posed during the interview with experts to assess what is the degree of risk that a user would normally associate with a bridge in good condition. Using data about the risks attributed to certain possibilities of death associated with as lightning, road accidents and diseases [HSE, 1988], they were asked to comparatively establish what they thought would be the acceptable level of risk to bridges in a pristine condition and in deteriorated conditions. On average, they experts suggested that a bridge in perfect conditions should have an annual risk of failure in the magnitude of 1 in 100.000.000 (10^{-8}). This value was seen as conservative by the author. A value of 10^{-6} (or 1 in a million) would be more in line with the recommendations of the HSE for "tolerable risk in normal circumstances".

Having established the acceptable level of risk in perfect condition, a simplified procedure was developed to estimate the evolution of the P_{fail} with changes (deterioration) in the Condition State of a certain element. An exponential curve was adopted to represent the fact that the risk increases more rapidly with the deterioration of the Condition State.

The minimum risk was associated with a notional Condition State of zero. To establish the curve another point was necessary, such as the maximum risk of failure in the worse Condition State. The values of the transition probabilities in the worse Condition State provided by PONTIS were used as an approximation of the risk at this point.

- *User Costs at Collapse*

The UCC can be taken as the sum of the potential monetary costs in terms of loss of lives and material damages in case of an accident. To exemplify how this could be used in practice consider a bridge that contain in average 15 cars. Assume that the average vehicle occupancy is 1.21, the probability of loss of life (P_{ll}) in the case of an accident is 25%, the monetary cost of a life is £1,000,000 and the average cost of material damages is £5,000. In these conditions a reduction in the probability of failure of 0.1% would represent a UCC of £7950, with the potential material costs representing £75 and the potential loss of lives £7875.

- *User Costs at Normal Use*

In systems like PONTIS the user costs due to deterioration and obsolescence are usually focused on the inadequacies and therefore are considered with more emphasis when improvement strategies are considered. Usually the costs appropriated are just the ones associated with restrictions of use and the increase in the number of accidents. There are however other cost and this thesis advocates that a broader view of user costs should be employed, especially for maintenance strategies.

A model was proposed to estimate the impact of changes in the Condition State in the User Costs incurred during the normal operation of the structure. The model considered that the worsening of the Condition State in a deteriorated bridge would be expressed in two ways: speed reductions and traffic diversions. These would in turn originate delays and increase the VOC and the number of accidents. Hypothetically, the model could be extended to cover other things, such as the psychological distress or discomfort caused by the existence of cracks. In this first version, however, the model will be limited to include just the traditional user costs components normally used in other systems, as discussed by Robinson [1976].

The intensity of the consequences of deterioration will depend on the type of the element and its effect on the functional performance of the bridge. The deterioration of the pavement will for example have a bigger impact on the reduction of speed than the deterioration of a column. The later however can lead to limitations in weight and impose the need to divert part of the traffic flow (usually the heavy vehicles). Structural deterioration may eventually also force authorities to limit speed in the bridge.

The first step to estimate this component of the cost if to determine if the deterioration or inadequacy is causing a reduction in speed. A simple relationship between the condition of the pavement and the speed of the flow was used to express the effect of deterioration in the functional performance of the structure. This relation was based on some data available in Brazil and has not been fully validated in practice. It should therefore be adjusted before implementation in practice. Nonetheless, it gives sensible results and was included as a first approximation. Given a certain speed reduction the traffic assignment model is run to check the results. It cost in time, VOC and accidents is calculated using the values defined by the user or assumed by the computer for lives, time, fuel and VOC. With this data, this component of the user cost can be calculated using procedures similar to those discussed in chapter 10.

In relation to detours, it will be necessary to input information in ORIGAM about any restriction of load. Depending on the load restriction, the number of heavy vehicles affected is estimated and the effects of this traffic rearrangement are determined with the help of the traffic assignment model.

- *Environmental Cost at Normal Use*

Based on the same data as the user costs at normal use, this model calculates the increase in emissions due to the detour of heavy vehicles in response to the posting of the bridge. The increase in the percentage of vehicles in the detour could hypothetically cause an increase in the noise impact but this was not considered in this first version of the model.

- *Fuzzy Rule Processing*

As discussed in chapter 8, the fuzzy rule-processing model was based on a similarity mechanism and used a set of linguistic variables going from "extremely low" to "extremely high". All variables were mapped into this set of terms. The membership function for the generic set was established based on interviews with 5 people. The mapping of people's opinion about the significance of the set of linguistic variables to a universe of discourse 0-1 is given below. As can be observed, the values are neither regular nor symmetric, demonstrating the tendency of people to be non-linear in their considerations

Extremely low (el): [1/0, 0.95/.1, 0.05/.2, 0.01/.3, 0/.4, 0/.5, 0/.6, 0/.7, 0/.8, 0/.9, 0/1]

Very low (vl): [.7/0, 1/.1, 0.7/.2, 0.15/.3, 0.05/.4, 0/.5, 0/.6, 0/.7, 0/.8, 0/.9, 0/1]

Low (l): [.5/0, 0.7/.1, 1/.2, 0.95/.3, 0.6/.4, 0.1/.5, 0.05/.6, 0/.7, 0/.8, 0/.9, 0/1]

Fairly low (fl): [.05/0, 0.2/.1, 0.5/.2, 1/.3, 0.9/.4, 0.65/.5, 0.25/.6, 0/.7, 0/.8, 0/.9, 0/1]

Slightly low (sl): [0/0, 0.05/.1, 0.3/.2, 0.5/.3, 1/.4, 0.8/.5, 0.6/.6, 0.1/.7, 0/.8, 0/.9, 0/1]

Medium (m): [0/0, 0/.1, 0.2/.2, 0.3/.3, 0.6/.4, 1/.5, 0.8/.6, 0.5/.7, 0.2/.8, 0/.9, 0/1]

Slightly high (sh): [0/0, 0/.1, 0/.2, 0/.3, 0.1/.4, 0.6/.5, 1/.6, 0.8/.7, 0.6/.8, 0.1/.9, 0/1]

Fairly high (fh): [0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0.2/.5, 0.25/.6, 1/.7, 0.85/.8, 0.5/.9, 0.2/1]

High (h): [0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0.05/.5, 0.1/.6, 0.5/.7, 1/.8, 0.7/.9, 0.3/1]

Very high (vh): [0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, 0.2/.7, 0.8/.8, 1/.9, 0.7/1]

Extremely high (eh): [0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, 0/.7, 0.05/.8, 0.95/.9, 1/1]

For reasoning purposes however it is suitable that very low or very high are the same as low and high. A tailed distribution was then used, as suggested in figure VII-4.

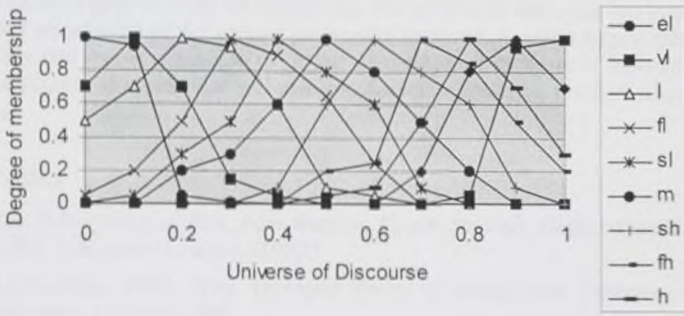

Figure VII-4 – Normal and tailed membership functions for generic fuzzy numbers.

Similarity Matrix

Based on the tailed membership functions discussed above the similarity matrix shown in table VII-4 was established.

Table VII-4 – Similarity matrix for determination of the firing strength of rules.

	Fuzzy Numbers										
	el	vl	l	fl	sl	m	sh	fh	H	vh	eh
el	1	1	1	.2	.2	.2	0	0	0	0	0
vl	1	1	1	.5	.4	.2	.1	0	0	0	0
l	1	1	1	.95	.6	.5	.1	.1	.1	0	0
fl	.2	.5	.95	1	.9	.6	.6	.25	.1	0	0
sl	.2	.4	.6	.9	1	.8	.6	.25	.1	.1	0
m	.2	.2	.5	.6	.8	1	.8	.5	.5	.2	.05
sh	0	1	.1	.6	.6	.8	1	.8	.6	.6	.1
fh	0	0	.1	.25	.25	.5	.8	1	.95	.8	.5
h	0	0	.1	.1	.1	.5	.6	.95	1	1	1
vh	0	0	0	0	.1	.2	.6	.8	1	1	1
eh	0	0	0	0	0	.05	.1	.5	1	1	1

- *Limitations*

The discussion about what is the best method to calculate each of the factors that are necessary to determine the various components of the appraisal model is beyond the scope of this thesis. The decision about which model to adopt must ultimately come from the user. The majority of models will require the use of local data or the customisation of the original data and methods to match the conditions prevalent in the portion of the network under the responsibility of the authority.

Therefore, no standard approach can be established. The interest of this work lies in analysing how, having produced an estimate of the various parameters involved, it would be possible to determine the MRI strategy that would maximise the effect of the budget in terms of increasing value. The thesis also investigates if reasonable and sensible decisions could be reached when approximate values are used.

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Data Used in the Validation and Verification Tests

This appendix presents the data used in the validation and verification of the appraisal model carried out in chapter 11. The exercise involved calculating the elements of the appraisal model for a particular bridge. Apart from the data contained in chapter 11 the following additional data was used in the calculations:

Characteristics of the bridge:

Length: 189 ft. (57.6 m) Deck area: 5670 sq. ft. Width: 30 ft (9 m)
Approach Width: 27 ft (8.2m) Roadway width: 2 x 13.5 ft (4.1 m) No median
Link Length: 3 km Number Spans: 2 ADT: 20,000 (peak 1760 v/h)
Under: river (13 m below) Maximum allowable speed: 80 km/h (50 m/h)
Detour length: 4.5 km (additional travel length 1.5 km)
Cars: 76% LGV: 4% VHGV: 5% HGV: 10% PSV: 5%

Characteristics of the bridge elements:

Table VIII-1 presents the characteristics of the bridge elements in terms of transition probabilities (TP) and time to change state (TTC), as extracted from the PONTIS V2.0 demonstration database. It also presents the replacement cost adjusted to 1998 values in pounds.

Table VIII-1 – Characteristics of the Bridge Elements

Element Code	12	104	205	215	302	321	331
Repl. Cost £ (Nov.98)	346/sq ft	3,460/un	45,350/un	34,600/lft	10,812/lf t	3,460/	692/lft
TP12/TTC	13% / 10y	1% 137.9y	1% 137.9y	1% 137.9y	3% 45.5y	1% 137.9y	3% 45.5y
TP23/TTC	14% / 92y	2% 68.6y	2% 68.6y	2% 68.6y	5% 27.0y	2% 68.6y	5% 27.0y
TP34/TTC	5% / 27y	2% 68.6y	2% 68.6y	2% 68.6y	6% 22.4y (Fail)	2% 68.6y	6% 22.4y (Fail)
TP45/TTC	9% / 14.7y	2% 68.6y (Fail)	2% 68.6y (Fail)	2% 68.6y (Fail)	-	2% 68.6y (Fail)	-
TP56/TTC	9% / 14.7y (Fail)	-	-	-	-	-	-

Characteristics of the MRI Activities

In the advanced model the unit cost must be divided in labour and material costs because the choice of access scheme and work strategy may affect the productivity, which will in turn affect the labour part of the costs, increasing the related and indirect costs. The labour percentage and basic productivity of each of the activities considered for intervening in the bridge example are given in table VIII-2 below.

Table VIII-2- Characteristics of the MRI activities

Strategy Number	I	II	III
Activity (CS=3)	Patch Potholes	Repair Potholes	Replace Overlay
Effect	50%(CS=2) 50%(CS=3)	100%(CS=2)	95%(CS=1) 5%(CS=2)
Labour Content	55%	40%	30%
Productivity (estimate)	30 m^2/h	5 m^2/h	10 m^2/h
Estimated Duration	16 h	95 h	48 h
Activity (CS=1,2,4)	NONE		
Activity (CS=5)	Replace if greater than 1%		
Effect	95% (CS=1) 5% (CS=2)		

Determination of intervention impact:

The determination of the intervention impact depends on the characteristics of the traffic flow on the main route and on the detour route before and during intervention, for each work method utilised. The first step was to estimate the hourly flow characteristics. Using a similar decomposition function to the one adopted in QUADRO the following distribution of the ADT in hourly intervals was calculated for a typical day of the week (Mon-Thurs):

Hourly Flows - Main Route:

1-243	2-243	3-161	4-161	5-161	6-161
7-161	8-1150	9-1760	10-1150	11-1150	12-1150
13-1150	14-1150	15-1150	16-1150	17-1150	18-1726
19-926	20-926	21-926	22-926	23-926	24-243

The hourly flows in the detour route were assumed as one third of the ones in the main road. To simplify the analysis it was assumed that these distributions would be valid during all the days during the work period. The division of the total hourly flows (including both directions) into one-way flows was made using the tidality factors given in the QUADRO manual. These tidality factors were assumed as valid for all the days when the work would be carried out. Taking the tidality factors for weekdays it was calculated that the one-way flow in the peak hour in the tidal direction of the main route would be:

Q_{peak}(main route, tidal direction) = 1127 vehicles.

After determining the flows, the hourly average speeds for the main route and the detour were estimated using the speed flow relationships given in QUADRO. The following data was assumed:

Diff. Speed Heavy/Light vehicles zero flow: 4
Total Carriageway Width: 12 m
Average sight distance 240 m

Pct Heavy Vehicles: 12%
Verge Friction: 0.5
Access Friction: 0.6

Bendiness: 75 degree/km (Main) 150 (Detour) Net Gradient: 0 m/km
Hiliness: 15 m/km (main) 20 (detour)

Having the information about flows and speeds before the intervention it was then necessary to calculate the impact of each different work method on them. Considering that:

1) there is just one lane in each direction therefore the strategies of shuttle and lane closure are the same

2) enclosure is not useful in this case, because of the nature of the MRI activities to be carried out

3) weekend work was not considered as a viable work strategy because the author wanted to maintain the flow constant to simplify the calculations

Five work strategies were therefore considered:

- Total Closure
- Direction Closure with 24 h Shuttle Service
- Shuttle off peak
- Shuttle nocturnal
- Direction Closure with Detour

The characteristics of a shuttle service for the bridge example were taken as:

Length of obstruction: 100 m
Maximum Shuttle Flow (100 m): 1360 vehicles (extracted from Ling and Bristow [1989]).
Shuttle Speed: V =17-15*Q/1000+4.5L (from QUADRO)

Having the basic information about the shuttle service it was necessary to check for each work strategy the hours of operation, the speed-flow relationships obtained, the delay caused, the number of vehicles detoured and the consequent impact on the speed-flow relationship of the detour rote. The results are summarised in table VIII-3. The detailed calculations for one of the work strategies are shown in the tables at the end of this Appendix.

Table VIII-3 – Summary of the External Impacts of each Work Strategy.

Work Strategy	Total Closure	Direction Closure	Shuttle Service	Shuttle Off Peak	Shuttle Nocturnal
Overflow vehicles (per day)	20000	9707	726	0	0
Δ Avg. Speed Main Prim.	-70.19 km/h	-20.19 km/h	-60.14 km/h	-42.26 km/h	-18.19 km/h
Δ Avg. Speed Main Sec	-70.38 km/h	-52.43 km/h	-60.11 km/h	-44.27 km/h	- 19.37 km/h
Δ Avg. Speed Detour Prim.	-9.41 km/h	0	-1.85 km/h	0	0
Δ Avg. Speed Detour Sec.	-8.74 km/h	-8.74 km/h	-1 km/h	0	0

External Environmental Impact during Interventions

The author used the atmospheric emission mode discussed in Appendix VII with the values for the environmental emissions presented in Appendix III to calculate this item. An average consumption of 6.5 m/l (10.4 km/l) was assumed. It was also defined that cars would not be fitted with catalytic converters.

External User Impact during Interventions

The costs calculated in this item refer to the impacts on the users of the road carried by the bridge and the users of the detour route(s). If there was a road passing under the structure it might be necessary to calculate the effects on its users also since, depending on the activity performed and the access scheme adopted, it could be necessary to close or partially block the road under the bridge to undertake the work. This was not the case in this example. It is also interesting to note that, since these values just depend on the ADT and the characteristics of the bridge they could have been calculated in advance of the actual analysis of MRI strategies.

The total closure work strategy generates a large amount of user costs because it implies the diversion of all the traffic onto the detour, making its capacity insufficient and generating additional costs because of the longer journey and reduced speeds. A shuttle service can significantly reduce the impacts. If it is maintained for 24 hours, the capacity will just be surpassed in the peak hours in the morning and afternoon. Around 3.6% of the flow (726 vehicles) would have to be detoured or delayed at these times. The off peak and nocturnal work strategies further reduce the impacts by avoiding working in the peak hours. They will however have other effects on the expenditure because they affect the work productivity, as discussed below.

Selection of Work Method

After calculating the ECI (sum of environmental and user costs of intervention) the next element of the appraisal model to be calculated is the agency expenditure, i.e. the Monetary Cost of the Intervention (MCI). As discussed in chapter 9, this will involve the consideration of Direct, Related and Indirect costs. The DC refers to the basic expenditure if the MRI activity were performed in ideal conditions. As discussed above, however, the use of certain work strategies and access schemes will have an impact on the productivity, affecting the costs and the duration of the work. The choice of the most probable work strategy to adopt will also help define the number of working hours per day, likewise impacting the duration and affecting the costs. It is therefore necessary to perform the work strategy selection task discussed in chapter 10 before calculating the agency expenditure.

As discussed in Appendix VII, to select the work method it is necessary to consider, beyond the cost, the technical adequacy and the impact on the environment and the users. To calculate these factors, the rules from Appendix VI and the following system of values were used:

Importance given to technical adequacy: Very High (assumed as given by the user)
Importance given to environmental adequacy: High (assumed as given by the user)
Importance given to functional adequacy: Fairly High (assumed as given by the user)
Importance given to cost adequacy: High (assumed as given by the user)

The technical adequacy is calculated taking into consideration the appropriateness of the work strategy for the current bridge and MRI activity. In the present case it does not affect much the adequacy of MRI strategies I and II, which do not have problems with continuity. The functional adequacy however tends to the side of the Off Peak and Nocturnal Shuttle work strategies, which cause less disruption. The cost adequacy favours the Off Peak because of the smaller number of hours of overtime.

To calculate the environmental adequacy, it is necessary to transform the environmental costs calculated before in a fuzzy value and determine the noise sensibility of the area, since pollution and noise are the two environmental impacts considered in the initial version of ORIGAMI. The Noise Sensibility of the bridge neighbourhood was defined as Medium (measured using the noise model discussed in Appendix VII and making use of the GIS component). In this way the environmental adequacy is not decisive in the selection of the work strategies.

In the case of strategy III the consideration of continuity is decisive to reduce the appropriateness of these two work strategies and the dispute is refocused between direction closure and 24 h shuttle. Shuttle is preferred because it reduces the external costs.

Direct Cost

DC = Unit Cost of Treatment * Area Affected

Related Costs

As discussed in Appendix VII, the model adopted for related costs in the initial version of ORIGAMI is based on the consideration of three things: haulage costs, set-up costs and access costs.

Haulage costs: not significant in strategies I and II because although the bridge is rural the MRI activities considered do not imply the need for significant intake or removal of materials. Strategy III (the replacement option) is only one slightly affected, because the volume of material to remove is not large. An estimate of the cost for a haulage distance of 20 miles is given in table 6.

Set-Up Costs: There will be some set-up costs associated with the provision of water/power and other facilities to allow the work to be carried, especially in strategies II and III, that are longer and involve more complex activities. Strategy I will have a small set-up cost because it takes just one day and does not demand expensive plant or involves sophisticated procedures.

To determine the set-up cost the best solution would be to link the BMS with a specialised cost aggregation routine. If this is not possible, the use of information extracted from similar cases using CBR could be implemented. As a rough estimate, standard values or percentages could be used. Values between 5% and 10% could be used depending on the number of things to consider: water and electricity supply, drainage, setting out of offices and workplaces, security and supervision, cleaning of the site, insurance.

To supply the needs of the test carried out in chapter 11 the following values were considered as approximations of the set-up costs based on data obtained from similar operations effectively executed in real bridges:

Strategy I: £ 900 + £ 19/hour (transport of plant / electricity provision / supervision)

Strategy II: £ 2565 + £ 22/hour (transport of plant / electricity provision / water provision / supervision / security / establishment and clearing of site / miscellaneous)

Strategy III: £ 3500 + £ 32/hour (transport of plant / electricity provision / water provision / supervision / tools and protective clothing / security / establishment and clearing of site / miscellaneous)

Access Costs: The related costs would also include the cost of providing the access scheme and the reduction in productivity caused by the use of specific access equipment. There is however no need for the use of special access schemes in the case under study.

Indirect Cost

Environmental Protection: Nil because protection is not necessary since the bridge is not located in a environmentally sensitive area.

Removal and Reconnection of Services: Nil. The bridge does not carry any service.

Traffic Management: In the bridge example, the traffic management costs for the strategies I and II would not be significant, because the work site is relatively small (100 m) and there is no need for detouring vehicles. Based on previous experiences a lump sum of £2000 (20 pounds per m) plus an hour rate of £6 (approximate cost of one operator to monitor the system) is considered adequate. For strategy III, the traffic management cost is greater because it is necessary to signal the detour route. A lump sum of 5000 plus an hour rate of £10 was assumed for this case.

Work Strategy Cost: The adoption of a certain work strategy may also generate additional costs. These are mainly a result of the need to work out-of-hours, paying more for the workforce. It was assumed for the present case that 30% of the unitary cost would refer to labour costs. It was also defined that the extra working during night hours would increase the labour cost in 50%. For each strategy therefore the work strategy cost was calculated as:

$$WSC = [Nh(extra) / Nh(total)] * 0.3 * 0.5 * DC$$

Variation in the Probability of Failure :.

After calculating the MCI it is necessary to determine he Bridge Utility. To do this it is necessary to determine the Value of Risk, which depends on the variations in the probability of failure for each year of the planning horizon for each strategy.

The probabilities of failure of each element at time T0 were determined. The transition probabilities were them applied and a new set of probabilities of failure was calculated for the new distribution of the condition states. Just element 12 was affect seriously because the others were assumed to be at perfect condition at T0. Figure VIII-1 shows the evolution of the P_{fail} of element 12 during the planning horizon if strategy 0 (do-nothing) was adopted.

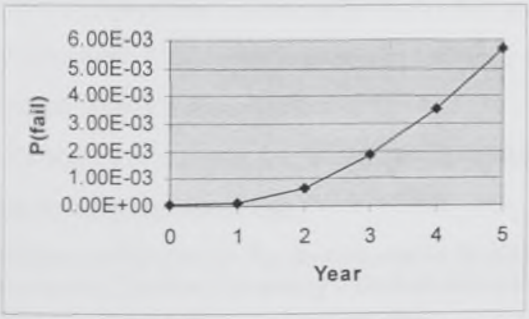

Figure VIII-1. Evolution of P_{fail} of element 12 during the planning horizon if no MRI action is taken (Strategy 0).

After calculating the risk for each element the risk for the whole bridge was calculated using a serial model that took into account the structural importance (ESI) of each bridge element Ex:

$$Pfail(bridge,t) = \Pi_x (ESI * Pfail(E_x, t))$$

The use of a series model was justified by the lack of redundancy on the bridge. The ESI values were taken from Appendix II.

Bridge Value

Asset Value: calculated using the replacement cost of the elements, as follows:

AV = 5670*346 + 378*3,460 + 1*45,340 + 2*34,600 + 60*10,812 + 2*3,460 + 458*692

AV = £ 4,356,816

Functional Value: calculated using the daily ECI associated with the Total Closure work strategy.

The value was aggregated for each year trough the multiplication of the daily ECI by 365 days. From year to year the ECI was adjusted to take into consideration the increase in the number of vehicles (defined as a being equal to 2.8%). The following values were calculated:

Year 0 - £ 7,686,407.25

Year 1 - £ 8,007,052.45

Year 2 - £ 8,343,082.40

Year 3 - £ 8,694,825.60

Year 4 - £ 9,067,140.20

Year 5 £ 9,459,544.40

Historic Value: Defined as nil because the historic relevance was defined as low, the standard value for bridges, which implies that no modification in the notional Bridge Value will be made because of the historic relevance.

Strategic Value: Calculated using a majoring factor determined using the strategic relevance function discussed in Appendix II with a strategic relevance of "High".

User Costs at Collapse

Average interval between vehicles in tidal direction (peak hour): 3.4 sec

Average interval between vehicles in other (peak hour): 5.11 sec

Average crossing time: 3.13 sec (at 40.74m/h - flow speed at peak hour)

Average number of cars simultaneously on the bridge: 2

Estimate number persons involved: 2.1*2 = 4.2

Estimate cost of accidents: 4.2 * £1,050,000 = £ 4,200,000

Determination of Value at Risk

Obtained multiplying the P_{fail} for each year in the planning horizon by the Bridge Value plus the User Cost at Collapse. For strategy I these are the results for a 5-year interval.

Year	Value at Risk	Var. Pfail	Potential Savings	Discounted Potential Savings
0	£48,158,388.83	-4.40E-05	£2,118.63	£2,118.63
1	£48,479,034.03	-1.36E-04	£6,612.87	£6,238.56
2	£48,815,063.98	-1.36E-04	£6,658.71	£5,926.23
3	£49,166,807.18	-6.09E-04	£29,918.07	£25,119.79
4	£49,539,121.78	-6.09E-04	£30,144.62	£23,877.36
5	£49,931,525.98	-1.72E-03	£85,881.89	£64,175.95

Opportunity Cost of Capital

Calculated using a return rate of 6% a.a.

Variation in Replacement Cost

Calculated using a discount rate of 6% a.a.

The following tables for the direction closure work strategy illustrated how the calculations were made.

TOTAL COST £ 20,178.01

Year	Main								Detour							
0	Total Flow (veh/h)	Tidal Factor	Flow Main (veh/h)	Flow Sec. (veh/h)	Speed Main (km/h)	Speed Sec. (km/h)	Crossing Time Main (min)	Crossing Time Sec (min)	Total Flow (veh/h)	Tidal Factor	Flow Main (veh/h)	Flow Sec. (veh/h)	Speed Main (km/h)	Speed Sec. (km/h)	Crossing Time Main (min)	Crossing Time Sec (min)
1	243	0.51	124	119	77.21	77.25	2.331304	2.3301	81	0.51	42	39	74.52	74.57	3.623188	3.620759
2	243	0.51	124	119	77.21	77.25	2.331304	2.3301	81	0.51	42	39	74.52	74.57	3.623188	3.620759
3	161	0.48	78	83	77.86	77.82	2.311842	2.31303	54	0.48	26	28	74.77	74.74	3.611074	3.612523
4	161	0.48	78	83	77.86	77.82	2.311842	2.31303	54	0.48	26	28	74.77	74.74	3.611074	3.612523
5	161	0.52	84	77	77.86	77.91	2.311842	2.31036	54	0.52	29	25	74.73	74.79	3.613007	3.610108
6	161	0.62	100	61	77.86	78.16	2.311842	2.30297	54	0.62	34	20	74.65	74.87	3.616879	3.606251
7	161	0.64	104	57	77.86	78.23	2.311842	2.30091	54	0.64	35	19	74.63	74.88	3.617848	3.605769
8	1150	0.64	736	414	70.06	72.6	2.569226	2.47934	384	0.64	246	138	71.3	73.01	3.786816	3.698124
9	1760	0.64	1127	633	65.25	69.14	2.758621	2.60341	587	0.64	376	211	69.25	71.86	3.898917	3.757306
10	1150	0.58	667	483	70.06	71.51	2.569226	2.51713	384	0.58	223	161	71.67	72.64	3.767267	3.71696
11	1150	0.53	610	540	70.06	70.61	2.569226	2.54921	384	0.53	204	180	71.97	72.34	3.751563	3.732375
12	1150	0.49	564	586	70.06	69.88	2.569226	2.57584	384	0.49	189	195	72.2	72.11	3.739612	3.74428
13	1150	0.47	541	609	70.06	69.52	2.569226	2.58918	384	0.47	181	203	72.33	71.98	3.732891	3.751042
14	1150	0.5	575	575	70.06	70.06	2.569226	2.56923	384	0.5	192	192	72.16	72.16	3.741685	3.741685
15	1150	0.5	575	575	70.06	70.06	2.569226	2.56923	384	0.5	192	192	72.16	72.16	3.741685	3.741685
16	1150	0.47	541	609	70.06	69.52	2.569226	2.58918	384	0.47	181	203	72.33	71.98	3.732891	3.751042
17	1150	0.45	518	632	70.06	69.16	2.569226	2.60266	384	0.45	173	211	72.46	71.86	3.726194	3.757306
18	1726	0.43	743	983	65.51	63.62	2.747672	2.8293	576	0.43	248	328	71.27	70.01	3.78841	3.856592
19	926	0.46	426	500	71.82	71.24	2.506266	2.52667	309	0.46	143	166	72.93	72.57	3.70218	3.720546
20	926	0.49	454	472	71.82	71.68	2.506266	2.51116	309	0.49	152	157	72.79	72.71	3.709301	3.713382
21	926	0.49	454	472	71.82	71.68	2.506266	2.51116	309	0.49	152	157	72.79	72.71	3.709301	3.713382
22	926	0.51	473	453	71.82	71.98	2.506266	2.50069	309	0.51	158	151	72.69	72.8	3.714404	3.708791
23	926	0.51	473	453	71.82	71.98	2.506266	2.50069	309	0.51	158	151	72.69	72.8	3.714404	3.708791
24	243	0.51	124	119	77.21	77.25	2.331304	2.3301	81	0.51	42	39	74.52	74.57	3.623188	3.620759
	20000		10293	9707					6677		3444	3233				

Length Site		100	m
Total capacity Shuttle (100 m)		0	veh
Maximum 1-way Shuttle flow		0	veh
Value of Time Loss		£ 4,120.03	per day
Time Loss	38560.5	1.446	

detour extra length =	1.5	km
link length	3	km
Minimum Shuttle Speed =	17.95	km/h

	No Vehicles	Flow Sec	Flow Passing Prim	Flow Passing	Blocked Flow Prim	Blocked Flc Sec	Speed Prim	Speed Sec	Avg Speed	Cross Time before Prim	Cross Time after Prim	LT Prim	LT (est ling)
1	124	119	0	0	124	119	17.95	17.95	#DIV/0!	4.66260847	20.05571	15.393	17.801
2	124	119	0	0	124	119	17.95	17.95	#DIV/0!	4.66260847	20.05571	15.393	17.801
3	78	83	0	0	78	83	17.95	17.95	#DIV/0!	4.62368353	20.05571	15.432	17.801
4	78	83	0	0	78	83	17.95	17.95	#DIV/0!	4.62368353	20.05571	15.432	17.801
5	84	77	0	0	84	77	17.95	17.95	#DIV/0!	4.62368353	20.05571	15.432	17.801
6	100	61	0	0	100	61	17.95	17.95	#DIV/0!	4.62368353	20.05571	15.432	17.801
7	104	57	0	0	104	57	17.95	17.95	#DIV/0!	4.62368353	20.05571	15.432	17.801
8	736	414	0	0	736	414	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
9	1127	633	0	0	1127	633	17.95	17.95	#DIV/0!	5.51724138	20.05571	14.538	17.801
10	667	483	0	0	667	483	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
11	610	540	0	0	610	540	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
12	564	586	0	0	564	586	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
13	541	609	0	0	541	609	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
14	575	575	0	0	575	575	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
15	575	575	0	0	575	575	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
16	541	609	0	0	541	609	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
17	518	632	0	0	518	632	17.95	17.95	#DIV/0!	5.13845275	20.05571	14.917	17.801
18	743	983	0	0	743	983	17.95	17.95	#DIV/0!	5.49534422	20.05571	14.56	17.801
19	426	500	0	0	426	500	17.95	17.95	#DIV/0!	5.01253133	20.05571	15.043	17.801
20	454	472	0	0	454	472	17.95	17.95	#DIV/0!	5.01253133	20.05571	15.043	17.801
21	454	472	0	0	454	472	17.95	17.95	#DIV/0!	5.01253133	20.05571	15.043	17.801
22	473	453	0	0	473	453	17.95	17.95	#DIV/0!	5.01253133	20.05571	15.043	17.801
23	473	453	0	0	473	453	17.95	17.95	#DIV/0!	5.01253133	20.05571	15.043	17.801
24	124	119	0	0	124	119	17.95	17.95	#DIV/0!	4.66260847	20.05571	15.393	17.801
	10293	9707	0	0	10293	9707							
						20000							
affected by shuttle:		0											

Value Time 10.6846 p/min
No. Occup C 2.1 persons
(using Quadro p.5-25)

Cross Time before Prim	Cross Time after Prim	LT Sec	Total LT Prim	Total LT Sec	Total Loss Time (min)	Cost Time
4.6601942	20.05571	15.4	0	0	0	0
4.6601942	20.05571	15.4	0	0	0	0
4.6260601	20.05571	15.4	0	0	0	0
4.6260601	20.05571	15.4	0	0	0	0
4.6207162	20.05571	15.4	0	0	0	0
4.6059365	20.05571	15.4	0	0	0	0
4.6018152	20.05571	15.5	0	0	0	0
4.9586777	20.05571	15.1	0	0	0	0
5.2068267	20.05571	14.8	0	0	0	0
5.0342609	20.05571	15	0	0	0	0
5.098428	20.05571	15	0	0	0	0
5.1516886	20.05571	14.9	0	0	0	0
5.1783659	20.05571	14.9	0	0	0	0
5.1384528	20.05571	14.9	0	0	0	0
5.1384528	20.05571	14.9	0	0	0	0
5.1783659	20.05571	14.9	0	0	0	0
5.205321	20.05571	14.9	0	0	0	0
5.6585979	20.05571	14.4	0	0	0	0
5.0533408	20.05571	15	0	0	0	0
5.0223214	20.05571	15	0	0	0	0
5.0223214	20.05571	15	0	0	0	0
5.0013893	20.05571	15.1	0	0	0	0
5.0013893	20.05571	15.1	0	0	0	0
4.6601942	20.05571	15.4	0	0	0	0
			0		0	£ -
					min	per day

DETOUR MAIN	Flow detour (before) veh/h	Speed (before) km/h	Flow detour (after) veh/h	Speed (after) km/h	speed vs adt (after)	travel time (before) (sec/veh)	travel time (after) (sec/veh)	Loss Time (vehicles detoured) (sec/veh)	Total LT (vehicles detoured) Min	Pot. LT (vehicles detoured) (sec/veh)	Effective LT (Veh. detoured0 (min)	Total LT Time (min)	Value Loss
1	42	74.52	166	72.57	12046.62	217.3913	223.2327	5.84143645	4.08900552	83.35448669	172.265939	176.35494	18.8428
2	42	74.52	166	72.57	12046.62	217.3913	223.2327	5.84143645	4.08900552	83.35448669	172.265939	176.35494	18.8428
3	26	74.77	104	73.54	7648.16	216.66444	220.2883	3.62384088	1.57033105	81.57777245	106.051104	107.62144	11.4989
4	26	74.77	104	73.54	7648.16	216.66444	220.2883	3.62384088	1.57033105	81.57777245	106.051104	107.62144	11.4989
5	29	74.73	113	73.4	8294.2	216.78041	220.7084	3.92803739	1.89855141	81.99794083	114.797117	116.69567	12.4685
6	34	74.65	134	73.07	9791.38	217.01273	221.7052	4.69248812	2.6590766	82.99470814	138.324514	140.98359	15.0635
7	35	74.63	139	72.99	10145.61	217.07088	221.9482	4.87732906	2.84510862	83.23770605	144.27869	147.1238	15.7196
8	246	71.3	982	59.7	58625.4	227.20898	271.3568	44.1478078	181.006012	117.2032013	1437.6926	1618.6986	172.951
9	376	69.25	1503	51.48	77374.44	233.93502	314.6853	80.7502966	506.035192	149.1680733	2801.87364	3307.9088	353.437
10	223	71.67	890	61.15	54423.5	226.036	264.9223	38.8863238	144.527504	110.7687395	1231.37915	1375.9067	147.01
11	204	71.97	814	62.35	50752.9	225.09379	259.8236	34.7297875	118.081278	105.6699939	1074.31161	1192.3929	127.402
12	189	72.2	753	63.31	47672.43	224.37673	255.8837	31.5070153	99.2470983	101.730164	956.263542	1055.5106	112.777
13	181	72.33	722	63.8	46063.6	223.97345	253.9185	29.9450403	90.3342049	99.76491265	899.546962	989.88117	105.765
14	192	72.16	767	63.09	48390.03	224.50111	256.776	32.2749256	103.279762	102.6224516	983.465161	1086.7449	116.114
15	192	72.16	767	63.09	48390.03	224.50111	256.776	32.2749256	103.279762	102.6224516	983.465161	1086.7449	116.114
16	181	72.33	722	63.8	46063.6	223.97345	253.9185	29.9450403	90.3342049	99.76491265	899.546962	989.88117	105.765
17	173	72.46	691	64.29	44424.39	223.57163	251.9832	28.4115754	81.9200424	97.82961848	844.595706	926.51575	98.9945
18	248	71.27	991	59.55	59014.05	227.30462	272.0403	44.735686	184.907502	107.1799756	1327.24536	1512.1529	161.567
19	143	72.93	569	66.21	37673.49	222.13081	244.676	22.5452204	53.7327754	94.30009096	669.530646	723.26342	77.2778
20	152	72.79	606	65.63	39771.78	222.55804	246.8383	24.2802924	61.5100742	96.46239628	729.898798	791.40887	84.5589
21	152	72.79	606	65.63	39771.78	222.55804	246.8383	24.2802924	61.5100742	96.46239628	729.898798	791.40887	84.5589
22	158	72.69	631	65.23	41160.13	222.86422	248.352	25.4877674	67.1177874	97.97604543	772.377825	839.49561	89.6967
23	158	72.69	631	65.23	41160.13	222.86422	248.352	25.4877674	67.1177874	97.97604543	772.377825	839.49561	89.6967
24	42	74.52	166	72.57	12046.62	217.3913	223.2327	5.84143645	4.08900552	83.35448669	172.265939	176.35494	18.8428
Total Bef	3444	Total Afte	13737	Avg Spe	62.63369	Avg Time (r	4.112346					20276.522	######
												3.0414782	per day

DETOUR SEC	Flow detour (before) veh/h	Speed (before) km/h	Flow detour (after) veh/h	Speed (after) km/h	speed vs adt (after)	travel time (before) (sec/veh)	travel time (after) (sec/veh)	Loss Time (vehicles detoured) (sec/veh)	Total LT (vehicles detoured) Min	Pot. LT (vehicles detoured) (sec/veh)	Effective LT (Veh. detoured0 (min)	Total LT Time (min)	Value Loss
1	39	74.57	158	72.69	11485.02	217.24554	222.8642	5.61867681	3.65213993	83.05839267	164.732479	168.38462	17.9912
2	39	74.57	158	72.69	11485.02	217.24554	222.8642	5.61867681	3.65213993	83.05839267	164.732479	168.38462	17.9912
3	28	74.74	111	73.43	8150.73	216.7514	220.6183	3.86687104	1.80453982	81.83647175	113.207119	115.01166	12.2885
4	28	74.74	111	73.43	8150.73	216.7514	220.6183	3.86687104	1.80453982	81.83647175	113.207119	115.01166	12.2885
5	25	74.79	102	73.57	7504.14	216.6065	220.1985	3.59195226	1.49664678	81.57696412	104.690437	106.18708	11.3457
6	20	74.87	81	73.91	5986.71	216.37505	219.1855	2.81044579	0.93681526	81.00739966	82.357523	83.294338	8.89967
7	19	74.88	76	73.98	5622.48	216.34615	218.9781	2.63194834	0.83345031	80.92364738	76.877465	77.710915	8.3031
8	138	73.01	552	66.48	36696.96	221.88741	243.6823	21.7948978	50.1282649	94.92197989	654.961661	705.08993	75.336
9	211	71.86	844	61.87	52218.28	225.43835	261.8393	36.4009882	128.010142	105.6345387	1114.44438	1242.4545	132.751
10	161	72.64	644	65.03	41879.32	223.01762	249.1158	26.0981716	70.0300937	98.08796444	789.608114	859.63821	91.8489
11	180	72.34	720	63.83	45957.6	223.94249	253.7992	29.8566602	89.5699807	100.8463145	907.61683	997.18681	106.545
12	195	72.11	781	62.87	49101.47	224.65677	257.6746	33.0177922	107.307825	103.1239083	1007.17684	1114.4847	119.078
13	203	71.98	812	62.38	50652.56	225.06252	259.6986	34.636104	117.185485	104.3476432	1059.12858	1176.3141	125.684
14	192	72.16	767	63.09	48390.03	224.50111	256.776	32.2749256	103.279762	102.6224516	983.465161	1086.7449	116.114
15	192	72.16	767	63.09	48390.03	224.50111	256.776	32.2749256	103.279762	102.6224516	983.465161	1086.7449	116.114
16	203	71.98	812	62.38	50652.56	225.06252	259.6986	34.636104	117.185485	104.3476432	1059.12858	1176.3141	125.684
17	211	71.86	843	61.89	52173.27	225.43835	261.7547	36.3163738	127.712581	105.5950963	1112.26835	1239.9809	132.487
18	328	70.01	1311	54.51	71462.61	231.39551	297.1932	65.7976606	359.693878	127.4352378	2087.81398	2447.5079	261.506
19	166	72.57	666	64.68	43076.88	223.23274	250.4638	27.2310811	75.3393244	98.8635973	823.863311	899.20264	96.0762
20	157	72.71	629	65.26	41048.54	222.80292	248.2378	25.4349023	66.5546609	97.5681751	767.536311	834.09097	89.1193
21	157	72.71	629	65.26	41048.54	222.80292	248.2378	25.4349023	66.5546609	97.5681751	767.536311	834.09097	89.1193
22	151	72.8	604	65.66	39658.64	222.52747	246.7256	24.1980834	60.8985098	96.68387765	729.963276	790.86179	84.5004
23	151	72.8	604	65.66	39658.64	222.52747	246.7256	24.1980834	60.8985098	96.68387765	729.963276	790.86179	84.5004
24	39	74.57	158	72.69	11485.02	217.24554	222.8642	5.61867681	3.65213993	83.05839267	164.732479	168.38462	17.9912
No.Vehic.	3233	No.Vehic.	12940	Avg.Spe	63.51899						16562.4772	18283.939	######
					km/h						2.48437158		1953.57

Cost of atmospheric emissions	£13,530.20					
petrol (80%)	9839.58 liters @		£ 1.15 =		£ 11,313.27	/day
diesel (20%)	2459.9 liters @		£ 0.90 =		£ 2,216.93	/day
Average Consumption	6.5 m/l	Average consumption site		0.00962 l/car		
Site Length	0.0625 miles (100 m)					
12299.475	0.461225					

MAIN ROUTE

Before Intervention				After Intervention				
number veh	Avg Speed	Rate Cons.	Total Cons.	number veh	Avg Speed	Rate Cons.	Total Cons.	Additional Cons.
243	77.229588	0.841955	1.96726	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
243	77.229588	0.841955	1.96726	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
161	77.839379	0.835451	1.29334	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
161	77.839379	0.835451	1.29334	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
161	77.883913	0.834991	1.29263	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
161	77.973665	0.834069	1.2912	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
161	77.990994	0.833892	1.29093	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	70.9744	0.930141	10.2852	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1760	66.649074	1.014001	17.16	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	70.669	0.935448	10.3439	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	70.318261	0.941658	10.4126	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	69.968278	0.947978	10.4824	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	69.774035	0.951538	10.5218	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	70.06	0.94631	10.464	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	70.06	0.94631	10.464	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	69.774035	0.951538	10.5218	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1150	69.565391	0.955404	10.5646	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1726	64.433598	1.064201	17.6616	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
926	71.506825	0.921111	8.20143	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
926	71.748639	0.917104	8.16575	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
926	71.748639	0.917104	8.16575	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
926	71.898272	0.914653	8.14393	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
926	71.898272	0.914653	8.14393	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
243	77.229588	0.841955	1.96726	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
			180.099				#DIV/0!	0 litres

DETOUR MAIN		Avg Consumption detour link	1.1077									
		Normal				Intervention			Take off consumption detoured			
number veh	Avg Speed	Rate Consumpt	Total Consump	Added Flow	number veh	Avg Spe	Rate Consumption	Total	Added Detour	Added Detoured	Old Detoured	Total Added
42	74.52	0.875351	40.724	124	166	72.57	0.90393	166.2116	54.12445	112.0871	77.09717	48.39038
42	74.52	0.875351	40.724	124	166	72.57	0.90393	166.2116	54.12445	112.0871	77.09717	48.39038
26	74.77	0.871962	25.1125	78	104	73.54	0.88924	102.4402	33.07965	69.36055	48.12199	29.20568
26	74.77	0.871962	25.1125	78	104	73.54	0.88924	102.4402	33.07965	69.36055	48.12199	29.20568
29	74.73	0.8725	28.0274	84	113	73.4	0.8913	111.5633	36.69414	74.8692	51.79512	31.74081
34	74.65	0.873581	32.9004	100	134	73.07	0.89624	133.0294	43.40552	89.62385	61.59279	38.53616
35	74.63	0.873852	33.8786	104	139	72.99	0.89745	138.18	44.84499	93.33501	64.0429	40.25852
246	71.3	0.924585	251.942	736	982	59.7	1.18791	1292.148	417.8502	874.2981	505.5386	534.6673
376	69.25	0.961331	400.387	1127	1503	51.48	1.45596	2423.97	783.1045	1640.866	843.8986	1179.685
223	71.67	0.9184	226.859	667	890	61.15	1.14763	1131.388	365.9178	765.47	460.7585	443.7703
204	71.97	0.913486	206.42	610	814	62.35	1.11589	1006.156	325.4626	680.6937	424.1808	375.5555
189	72.2	0.90978	190.466	564	753	63.31	1.09154	910.4418	294.8155	615.6263	394.8255	325.1504
181	72.33	0.907708	181.989	541	722	63.8	1.07946	863.3023	279.3144	583.9879	380.1468	301.1669
192	72.16	0.910421	193.625	575	767	63.09	1.09704	932.0418	301.2461	630.7957	401.8177	336.5986
192	72.16	0.910421	193.625	575	767	63.09	1.09704	932.0418	301.2461	630.7957	401.8177	336.5986
181	72.33	0.907708	181.989	541	722	63.8	1.07946	863.3023	279.3144	583.9879	380.1468	301.1669
173	72.46	0.905654	173.551	518	691	64.29	1.06762	817.1759	264.1466	553.0293	365.4642	278.1605
248	71.27	0.925092	254.13	743	991	59.55	1.19219	1308.696	422.8977	885.7981	583.9025	470.6633
143	72.93	0.898366	142.301	426	569	66.21	1.02356	645.1263	209.0897	436.0366	289.7674	213.0577
152	72.79	0.900514	151.619	454	606	65.63	1.03648	695.7508	225.1878	470.563	307.4696	236.6624
152	72.79	0.900514	151.619	454	606	65.63	1.03648	695.7508	225.1878	470.563	307.4696	236.6624
158	72.69	0.90206	157.874	473	631	65.23	1.04559	730.8195	236.2552	494.5643	319.4813	253.4638
158	72.69	0.90206	157.874	473	631	65.23	1.04559	730.8195	236.2552	494.5643	319.4813	253.4638
42	74.52	0.875351	40.724	124	166	72.57	0.90393	166.2116	54.12445	112.0871	77.09717	48.39038
3402			3442.75	10169	13571			17065.22	5520.769	11544.45		6390.611
												liters/day

DETOUR SEC		Avg Consumption detour link		1.1077								
		Normal					Intervention		Take off consumption detoured			
number	Avg Speed	Rate	Total	Added	number	Avg Spe	Rate	Total	Var		Old	Total
car+lgv		Consumpt	Consump	Flow	car+lgv		Consumption		consump		Detoured	Added
39	74.57	0.874668	37.7857	119	158	72.69	0.90206	157.8744	50.52924	107.3451	76.92317	43.16554
39	74.57	0.874668	37.7857	119	158	72.69	0.90206	157.8744	50.52924	107.3451	76.92317	43.16554
28	74.74	0.872366	27.0568	83	111	73.43	0.89086	109.5342	35.59314	73.94109	53.44459	29.03288
28	74.74	0.872366	27.0568	83	111	73.43	0.89086	109.5342	35.59314	73.94109	53.44459	29.03288
25	74.79	0.871694	24.1392	77	102	73.57	0.8888	100.4206	31.98307	68.43748	49.61172	26.66961
20	74.87	0.870624	19.2877	61	81	73.91	0.88388	79.30462	25.38781	53.91681	39.35148	20.66546
19	74.88	0.870491	18.3205	57	76	73.98	0.88288	74.32527	24.00087	50.3244	36.78247	19.22231
138	73.01	0.897148	137.139	414	552	66.48	1.01766	622.2438	200.9329	421.3109	282.667	202.4374
211	71.86	0.915278	213.922	633	844	61.87	1.12841	1054.946	340.6596	714.2863	449.3706	391.6539
161	72.64	0.902837	161.011	483	644	65.03	1.0502	749.1674	241.9186	507.2487	327.5722	260.5846
180	72.34	0.90755	180.951	540	720	63.83	1.07873	860.3274	277.8141	582.5134	364.2703	315.1057
195	72.11	0.911224	196.824	586	781	62.87	1.10258	953.8543	307.7398	646.1145	393.6968	363.3331
203	71.98	0.913324	205.371	609	812	62.38	1.11512	1002.987	323.8812	679.1058	408.2174	389.3981
192	72.16	0.910421	193.625	575	767	63.09	1.09704	932.0418	301.2461	630.7957	386.5787	351.8377
192	72.16	0.910421	193.625	575	767	63.09	1.09704	932.0418	301.2461	630.7957	386.5787	351.8377
203	71.98	0.913324	205.371	609	812	62.38	1.11512	1002.987	323.8812	679.1058	408.2174	389.3981
211	71.86	0.915278	213.922	632	843	61.89	1.12789	1053.205	340.3793	712.8252	422.6756	416.6074
328	70.01	0.947218	344.146	983	1311	54.51	1.34929	1959.415	633.0652	1326.35	671.5317	943.7374
166	72.57	0.903928	166.212	500	666	64.68	1.05838	780.7878	251.6002	529.1876	331.7045	282.8717
157	72.71	0.90175	156.821	472	629	65.26	1.0449	728.0233	234.8296	493.1936	313.8776	257.3244
157	72.71	0.90175	156.821	472	629	65.26	1.0449	728.0233	234.8296	493.1936	313.8776	257.3244
151	72.8	0.90036	150.596	453	604	65.66	1.03581	693.0019	223.7819	469.22	301.7599	240.6464
151	72.8	0.90036	150.596	453	604	65.66	1.03581	693.0019	223.7819	469.22	301.7599	240.6464
39	74.57	0.874668	37.7857	119	158	72.69	0.90206	157.8744	50.52924	107.3451	76.92317	43.16554
No.Vehic.						Avg Spe				0		5908.864
			3218.39					15692.8	5065.733	10627.06	6527.76	liters/day

ACC Cost £ 1,382.13 per day

Prob. Acc Main Route Before:	0.3	per 10^6 vehkm
Prob Acc Main Route After (no sl	0.35	per 10^6 vehkm
Prob. Acc Detour Before:	0.25	per 10^6 vehkm
Prob Acc. Dir Closure	0.4	per 10^6 vehkm
Prob. Acc Shuttle	1	per 10^6 vehkm
Prob Acc. Detour Shuttle	0.3	per 10^6 vehkm
Length Detour	4.5	km
Length Link	3	km
Site Length	0.1	km

Avg Delay	30	min
Prob Slight	1.058	
Cost Slight	£ 1,500.00	
Cost Serious	£43,826	
Prob Serious	0.457	
Prob casualties	0.055	
Cost Fatalities	£1,025,000.00	

	no veh.	vehicles affected	PIA	PIA* Site On	PIA* Site Off	Risk	Cost Casualties	Cost Serious	Cost Slight	Sum Costs	Delay	Total Sum Sum
Bef Main	20000	-	0.3	-	-	0.018	£ 1,014.75	£360.51	£ 28.57	£1,403.83	£ 48.08	£ 1,451.91
BefDetour	6677	-	0.25	-	-	0.007512	£ 423.47	£150.45	£ 11.92	£ 585.84	£ 6.70	£ 592.53
												£ 2,044.44 before
Main after	0	0	0.3	1	0.35	0	£ -	£0.00	£ -	£ -	£ -	£ -
Detour after	26677	26677	0.25	0.35	0.25	0.042016	£ 2,368.67	£841.52	£ 66.68	£3,276.87	£ 149.70	£ 3,426.57
												£ 3,426.57 after
												£ 1,382.13 diff