A Risk-Based Decision Making Tool for Sustainable Bridge Management

by

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Abstract

The objective of this work is to provide support for evaluating the sustainability of bridge maintenance activities by developing a methodology in which optimal bridge maintenance plans are determined based on the trade-offs between economic and environmental impacts related to various maintenance activities.

For this, a variety of tools such as generation of maintenance plans using time and/or performance based approach, whole life costing, life cycle assessment, multi-criteria decision aid/analysis and uncertainty analysis were integrated into a stand-alone computer program, suitable for decision support. Direct impacts related to maintenance activities themselves, as well as indirect impacts arising from traffic disruption were considered quantitatively. The program can execute a deterministic analysis based on fixed input data as well as ascertain the influence of uncertainty on optimal maintenance plans within a probabilistic framework.

In order to explore and demonstrate the validity of the proposed methodology a number of case studies were carried out. These dealt with a single span simply supported reinforced slab bridge. Four alternative maintenance options commonly used were considered, for relevant cost and environmental data were collected or, where necessary, generated using whole life costing and life cycle assessment principles. The main conclusions from this work are:

1) Delaying the application of essential maintenance by applying appropriate preventative maintenance options can be justified in terms of sustainability.

2) Indirect impacts from traffic disruption are much larger than direct impacts, thus dominating total impacts.

3) Different optimal maintenance plans may be obtained depending on the types of

impact included. The initial bridge condition and the effectiveness of maintenance options in mitigating deterioration influence the choice of optimal maintenance plans. The required life-span is also a significant factor in determining optimal maintenance plans.

4) For cases where the optimal plan is not unique, the decision maker's relative preference between cost and environmental impact, i.e. the relative weight attached to cost and environmental impact criteria, plays an important role in choosing an optimal plan.

5) Probabilistic analysis can be used to increase confidence in the generation of optimal plans and will also produce additional options that are not apparent from a deterministic analysis.

In summary, given that sustainability concepts are becoming increasingly important in infrastructure maintenance and management, it is hoped that the methodology, possibilities and limitations presented in this study will enable decision-makers to gain a better understanding of the factors that should be considered, and help pave the way towards sustainable bridge maintenance.

Acknowledgements

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Declaration

I declare that the work presented in this thesis is original and appropriate for the subject area.

Notations

a, b, c	Parameters defined for calculating vehicle operating cost of fuel consumption in pence/km per vehicle
a, b, c	Parameters defined for calculating the amount of fuel consumption in litres per kilometre per vehicle
a1, b1	Parameters defined for calculating vehicle operating cost of non-fuel elements in pence/km per vehicle
AP_f, AP_{se}, AP_{sl}	Proportions of fatal, serious and slight accident, respectively
C	Cost at current price levels
C	Live load capacity factor
CC_f, CC_{se}, CC_{sl}	Costs per fatal, serious and slight casualty, respectively
C_{Di}	Direct cost of i_{th} maintenance plan
C_{Ii}	Indirect cost of i_{th} maintenance plan
C_{Ti}	Total cost of i_{th} maintenance plan
D_f, D_{se}, D_{sl}	Damage to property costs of fatal, serious and slight accident, respectively
DF	Demanding flow in main route
D_{do}	Damage to property cost per damage only accident
E_{Di}	Direct environmental score of i_{th} maintenance plan
E_{Ii}	Indirect environmental score of i_{th} maintenance plan
E_{jd}	Direct environmental score related to j_{th} maintenance option
E_{ji}	Indirect environmental score related to j_{th} maintenance option
E_{Ti}	Total environmental score of i_{th} maintenance plan
FDIV	Diverting flow
FMAIN	Flow in main route

I_{do}	Insurance administration cost per damage only accident
I_f, I_{se}, I_{sl}	Insurance administration costs of fatal, serious and slight accident, respectively
JT	Journey time on main route in the presence of site works
K, K_1, K_2, K_3	Constants used for calculating journey time on the main route
NC_f, NC_{se}, NC_{sl}	Average number of fatal, serious and slight casualty per PIA, respectively
N_{do}	Number of damage only accidents per PIA
NF	Normal flow in diversion route
P_{do}	Police cost per damage only accident
P_f, P_{se}, P_{sl}	Police costs of fatal, serious and slight accident, respectively
PV	Present value of future cost
QD	Actual queue
Qi	Start queue
QR	Equilibrium queue
r	Test discount rate
s_{Ci}	Relative strength of preference for whole life cost of ith maintenance plan
s_{Ei}	Relative strength of preference for environmental score of ith maintenance plan
S_i	Overall weighted performance score of ith maintenance plan
Spd_Div	Difference between time taken to travel 1m when travelling at Vq and Va
t	Time period in years
TA	Travel time on approach to site
TD	Travel time downstream of site
t_d	Time during which the deterioration process of reliability index is suppressed
TFDIV	Total flow in diversion

t_i	Time of damage initiation
t_p	Time interval of reapplication of preventative maintenance
t_{pd}	Duration of preventative maintenance option on reliability
t_{pi}	Time of first application of preventative maintenance
TS	Travel time through site
V	Average vehicle speed in kilometres per hour
Va	Speed on approach to site
Vq	Speed through queue
w_C	Weighting factor for whole-life cost
w_{DC}	Weighting factor for direct cost
w_{DE}	Weighting factor for direct environmental score
w_E	Weighting factor for environmental score
w_{IC}	Weighting factor for indirect cost
w_{IE}	Weighting factor for indirect environmental score
Y	Price index factor
α	Reliability index deterioration rate
β_0, β_{max}	Initial or maximum reliability index
β_{min}	Allowable minimum/target reliability index
γ	Increase in reliability (if any) immediately after the application of preventative maintenance action
ρ	Traffic intensity
θ	Reduced deterioration rate of reliability index during preventative maintenance action

Abbreviations

AADT	Annual Average Daily Traffic
AAHT	Annual Average Hourly Traffic
AGA	American Galvanizers Association
BA	A document reference representing Advice Notes related to bridges published by the Highways Agency in the UK
BBA	British Board of Agrement
BCA	British Cement Association
BCC	British Ceramic Confederation
BCSA	British Constructional Steelwork Association
BD	A document reference representing Design Manual related to bridges published by the Highways Agency in the UK
BDA	Brick Development Association
BEES	Building for Environmental and Economic Sustainability
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BS	British Steel plc.
BSI	British Standards Institute
BSRIA	Building Services Research and Information Association
BUWAL	Swiss Agency for Environment, Forests and Landscape
CBPP	Construction Best Practice Programme
CC	Construction Confederation
CIB	International Council for Research and Innovation in Building and Construction
CIRIA	Construction Industry Research and Information Association
CML	Institute of Environmental Science of Leiden University
COBA	COst Benefit Analysis
CP	Cathodic Protection
CR	Concrete Repair

CSI	Cement Sustainability Initiative
DALY	Disability Adjusted Life Years
DANTES	Demonstrate and Assess New Tools for Environmental Sustainability
DETR	Department of Environment, Transport and the Regions
DETRA	Department for the Environment, Food and Rural Affairs
DMRB	Design Manual for Roads and Bridges
DQI	Data Quality Indicator
DTI	Department of Trade and Industry
DTLR	Department for Transport, Local Government and the Regions
ECCS	European Convention for Construction Steelwork
EDIP	Environmental Design of Industrial Products
EER	Econo-Environmental Return
ELU	Environmental Load Units
EPA	Environmental Protection Agency
EPS	Environmental Priority Strategies in Product Development
GA	Galvanizers Association
GCCP	Government Construction Clients' Panel
GGBS	Ground Granulated Blastfurnace Slag
HA	Highways Agency
HALE	Healthy Years Life Expectancy
ICE	Institution of Civil Engineers
ISO	the International Organisation for Standardization
IUCN	the International Union for the Conservation of Nature and Natural Resources; The World Conservation Union
IVAM	IVAM Environmental Research in the Netherlands
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCECA	Life Cycle Environmental Cost Analysis
LCI	Life Cycle Inventory analysis

LCIA	Life Cycle Impact Assessment
LGV	Light Goods Vehicle
M4I	Movement for Innovation
MAUT	Multi Attribute Utility Theory
MAVT	Multi Attribute Value Theory
MCDA	Multi Criteria Decision Aid/Analysis Technique
NATS	the Highways Agency's National Structures database
OGV	Other Goods Vehicle
PAF	Potentially Affected Fraction of species
PDF	Potentially Disappeared Fraction of species
PFA	Pulverised Fuel Ash
PIA	Personal Injury Accident
PSV	Public Service Vehicle
QUADRO	QUeues And Delays at ROadworks
RE	Replacement of Element
RIBA	the Royal Institute of British Architects
SBI	Danish Building Research Institute
SCC	Self Compacting Concrete
SCI	Steel Construction Institute
SETAC	Society of Environmental Toxicology and Chemistry
SMART	Simple Multi Attribute Rating Technique
STPR	Social Time Preference Rate
TCAce	Total Cost Assessment
TRL	Transport Research Laboratory
UK	United Kingdom
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environmental Programme
UNEP	United Nations Environmental Programme
USA	United States of America
UTA	Utility Theory Additive

VOC	Vehicle Operating Cost
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development
WF	Waterproofing
WLC	Whole Life Costing

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Chapter 1

The application of sustainability concepts to infrastructure management

1.1 Introduction

The purpose of this thesis is to apply the principles of sustainable development to infrastructure management. More specifically, it aims to develop a new decision making support tool for bridge maintenance taking account of sustainability.

The starting point for this should be the understanding of sustainability concept and its historical development. Therefore, as a first step, this chapter tries to answer the following questions.

1) What is sustainability and sustainable development?
2) What is the background/history of sustainable development?
3) What is the principle of sustainable development?

Recently, many countries, especially developed countries, are trying to implement sustainable development principles into their various industry sectors. In particular, the construction industry has a huge impact on achieving sustainability targets because of its tremendous scale of business. The UK construction industry is no exception.

In order to embody sustainability in infrastructure management in the UK, it is necessary to understand the UK government policy for sustainable development and corresponding efforts in the construction industry. Therefore, this chapter also reviews the UK government's initiatives for sustainable construction and the accompanying efforts and researches undertaken in the construction industry.

Finally, this chapter discusses the specific characteristics of infrastructure management, and emphasises the necessity of so-called 'sustainable infrastructure management'.

1.2 Sustainability, sustainable development and sustainable construction

1.2.1 The principle of sustainable development

According to English dictionary [1], '*sustainable*' means "involving the use of natural products and energy in a way that does not harm the environment" and "that can continue or be continued for a long time".

Actually, the advent of sustainability is related with the anxiety over the threatening environmental destruction accumulated through human history and with the recognition for the necessity of immediate and overall efforts to preserve the "Earth" – our planet.

Many people agree that the publication of "Silent Spring" in 1962 was a turning point to attract people's attention to sustainable development [2]. Rachel Carson, the author of "Silent Spring", showed the critical damage from the use of pesticides and insecticides and urged choosing 'the other road' where the development is balanced with the preservation of the environment.

Also, in 1960s, a number of unprecedented environmental disasters and harmful effect of industrialisation were reported. All of these fueled the international debate and concerns about the environment, and a consensus for the necessity of "sustainable development" has gradually been reached.

Initial efforts for sustainable development were undertaken by the United Nations (UN). The UN hosted a series of conferences in order to promote international consensus for sustainable development and produced several documents which identified routes towards sustainable development. (See Table 1.1)

Table 1.1 UN's history for sustainable development

Year	History
1972	- Stockholm conference on the Human Environment
1979	- Geneva Convention on Air Pollution
1980	- World Conservation Strategy
1983	- Helsinki Protocol on Air Quality
1983	- The World Commission on Environment and Development
1987	- Montreal Protocol on Ozone Layer
1987	- Our Common Future (Brundtland Commission)
1990	- Green Paper on the Urban Environment
1992	- Earth Summit (Rio)
1996	- Habitat Conference
1996	- Kyoto Conference on Global Warming
2000	- The Hague Conference on Climate Change
2002	- World Summit

In 1983, UN formed the World Commission on Environment and Development (WCED). The aim of the World Commission was to find practical ways of addressing the environmental and developmental problems of the world. After three years of public hearings and over five hundred written submissions, the final report called "Our Common Future" was written in 1987. This report is also known as the Brundtland Report, after the Chair of the Commission and former Prime Minister of Norway, Gro Harlem Brundtland [3].

The Brundtland Report takes up a significant position in the history of "sustainable development" because it is the first internationally endorsed document which contains the definition, objectives and/or principles of sustainable development. According to this report, sustainable development is "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*".

A key to achieving sustainable development is equitable sharing of the environmental costs and benefits of economic development between and within countries and between present and future generation. This comment is known as "the twin principles of intra- and intergenerational equity". The principle of *intergenerational equity* requires that the next generation receive a stock of assets (resource potentials, created wealth, human capabilities) that is at least equivalent to our own, taking into account population growth. On the other hand, the principle of *intragenerational equity* requires a real improvement in the quality of life for those who are especially poor and disadvantaged.

Although inter- and intragenerational equity are aggregate yardsticks of progress towards sustainable development, they are open to wide interpretation and not readily applicable to specific development initiatives and proposals. For specific proposals, the fundamental requirement of sustainable development is the *integrated decision making* in which environmental, economic and social factors are balanced. This approach for integrated decision making is also known as the "three bottom line" approach (Figure 1.1).

In the schematic diagram, sustainable development lies in the common area which unifies three sets of economic, environmental and social goals. It is desirable to satisfy these three aspects at the same time, but usually no methodology is available to simultaneously optimise these three objectives. Therefore, the application of sustainable development requires a trade-off among economic, social and environmental objectives.

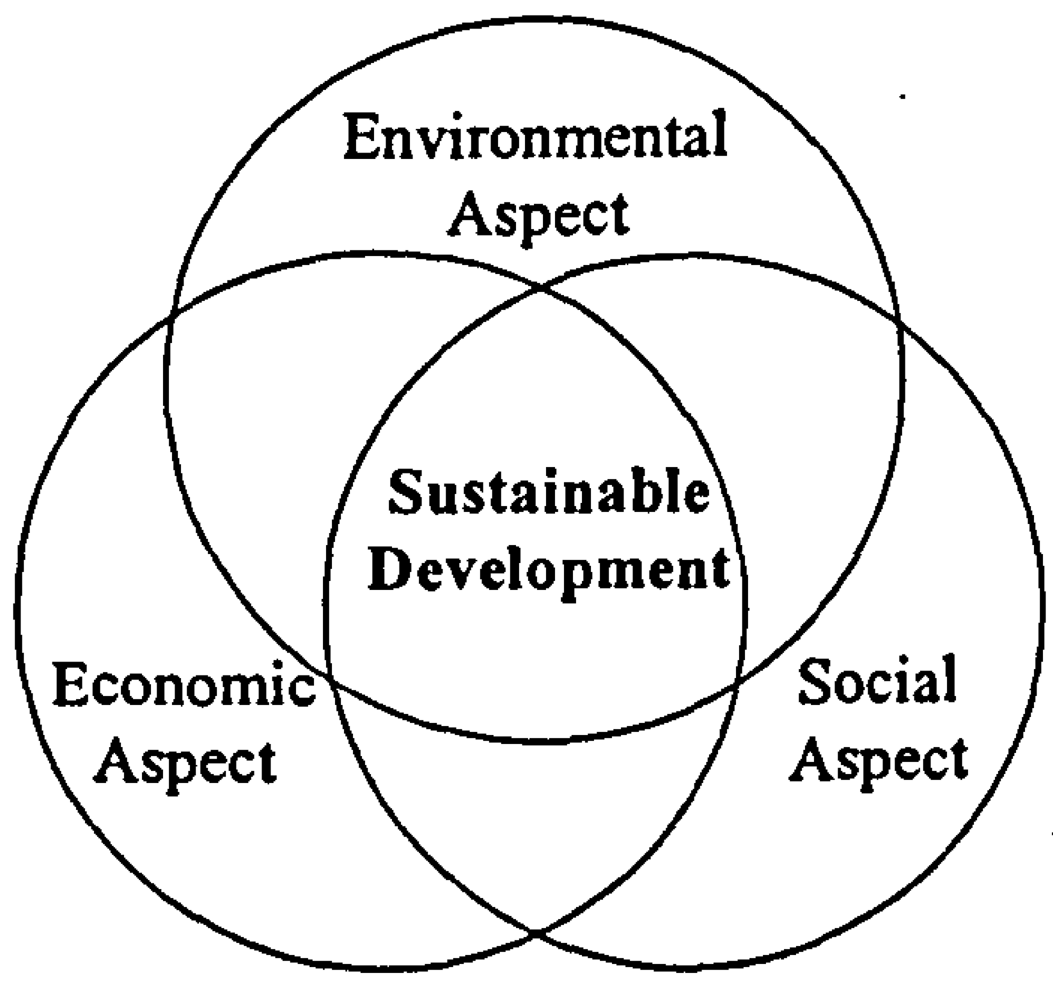


Figure 1.1 Three bottom line approach for sustainable development ([4])

However, it is also acknowledged that such a framework, i.e. the integration of three aspects, must be flexible enough to foster diversity and innovation if the vitality of interdisciplinary research collaboration is to be maintained in the longer term. In other words, if an engineering research incorporates socioeconomic and environmental components, so the technological options developed match societal needs and aspirations whilst at the same time benefiting the environment, it could be considered that such a research contributes effectively to the objectives for sustainable development [5]. Therefore, if necessary, the present research will choose such a flexible approach in developing a decision making framework for bridge maintenance taking account of sustainability. They will be discussed in the section 2.2.4 in more detail.

1.2.2 Sustainable construction – Sustainable development in the construction industry

Increasingly, sustainable development is the main objective for future development. All industries are required to take part, but the construction industry will play a vital role in achieving sustainability targets in one country due to its immense economic, environmental and social impacts on society.

Hence, sustainable construction, i.e., sustainable development in the construction industry has a potential to bring about huge economic, environmental and social benefits. In the following paragraphs, the efforts for sustainable construction in the UK are reviewed and the necessity for sustainable infrastructure management will be emphasised.

1.3 UK efforts for sustainable construction

Sustainable construction encompasses the complete life-cycle of a structure from initial concept through to demolition. This involves all those that develop, plan, design, build, alter, or maintain the built environment and includes building materials manufacturers and suppliers as well as clients and end use occupiers. In other words, promoting and delivering sustainable construction involves all stakeholders within the industry. In the following paragraphs, the initiatives for sustainable construction presented by the UK government are reviewed and the efforts of the construction industry for sustainable construction are analysed.

1.3.1 UK government policy for sustainable construction

In the UK, it was the government who led the way to sustainable construction. The UK government published key documents [6, 7] to suggest guidelines for sustainable construction, used legislation [8] and procurement [9] to enforce the construction industry to adopt sustainable practices, introduced sustainability concept in managing the Government estate [10] and promoted awareness and educated people by collecting information on sustainability initiatives and practical examples and publishing them[8, 11-14]. Table 1.2 shows the key documents published by the UK government for sustainable construction.

In 1999, the UK government published *A better quality of life – A strategy for sustainable development for the United Kingdom* in order to show the UK strategy for sustainable development [6]. According to this document, sustainable development can be achieved by meeting four objectives all at the same time. These are:

- social progress which recognises the needs of everyone;
- effective protection of the environment;
- prudent use of natural resources; and
- maintenance of high and stable levels of economic growth and employment.

Furthermore, in 2000, the Department of Environment, Transport and the Regions (DETR) published *Building a Better Quality of Life: A Strategy for more Sustainable Construction* [7]. This is the main sustainable construction policy document, released following extensive consultation with industry.

Table 1.2 Key documents for sustainable construction in the UK

Year	History
April 1999	Towards more sustainable construction: Green guide for managers on the Government estate.
May 1999	A better quality of life – A strategy for sustainable development for the United Kingdom.
April 2000	Building a Better Quality of Life: A Strategy for more Sustainable Construction.
June 2000	Achieving sustainability in construction procurement.
Oct 2001	Building a Better Quality of Life: report on progress 2001.
Jan 2002	Reputation, Risk & Reward – the business case for sustainability.
Jan 2003	EU legislation study report.
May 2003	Demonstrations of sustainability.
July 2003	Sustainable Construction Brief.
Oct 2003	Better Building Summit – Issue Paper.
Nov 2003	The UK Construction Industry: progress towards more sustainable construction 2000 – 2003.
April 2004	Sustainable Construction Brief 2.

To make the sustainable construction practice successful, this strategy implies that four consecutive steps are required. These steps are aiming, practical action, measuring progress and reporting. (See Figure 1.2)

Because of the complexity of the construction industry and the multi-dimensional characteristics of sustainable development, it is impossible to make a single comprehensive standard to cover the above steps. In other words, any aim, practical action, indicators for measuring progress and reporting type should be elaborated according to the construction stage, different levels (project, company, sector and industry) and sustainability issues. (See Figure 1.3)

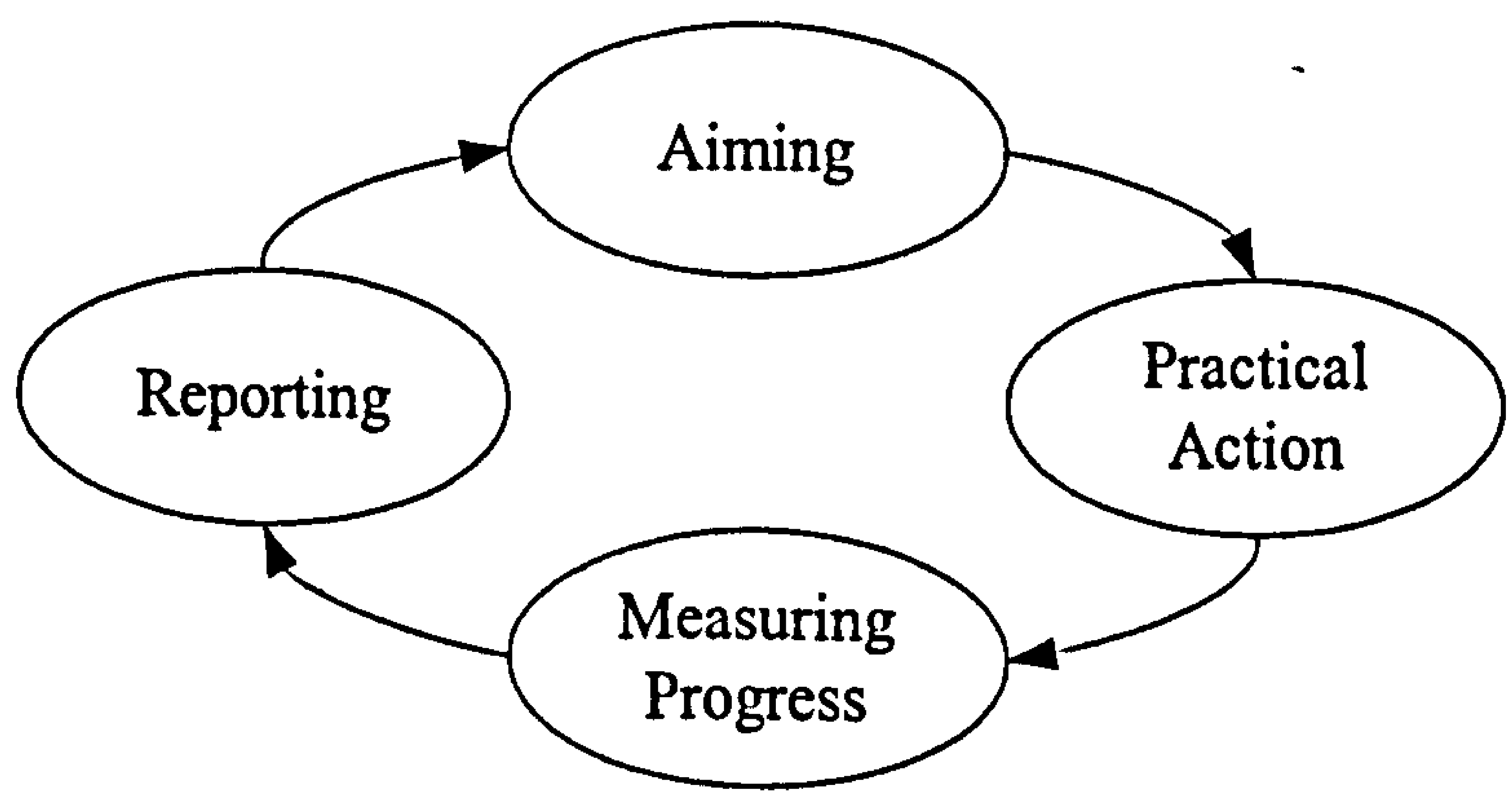


Figure 1.2 Four steps for effective application of sustainable construction

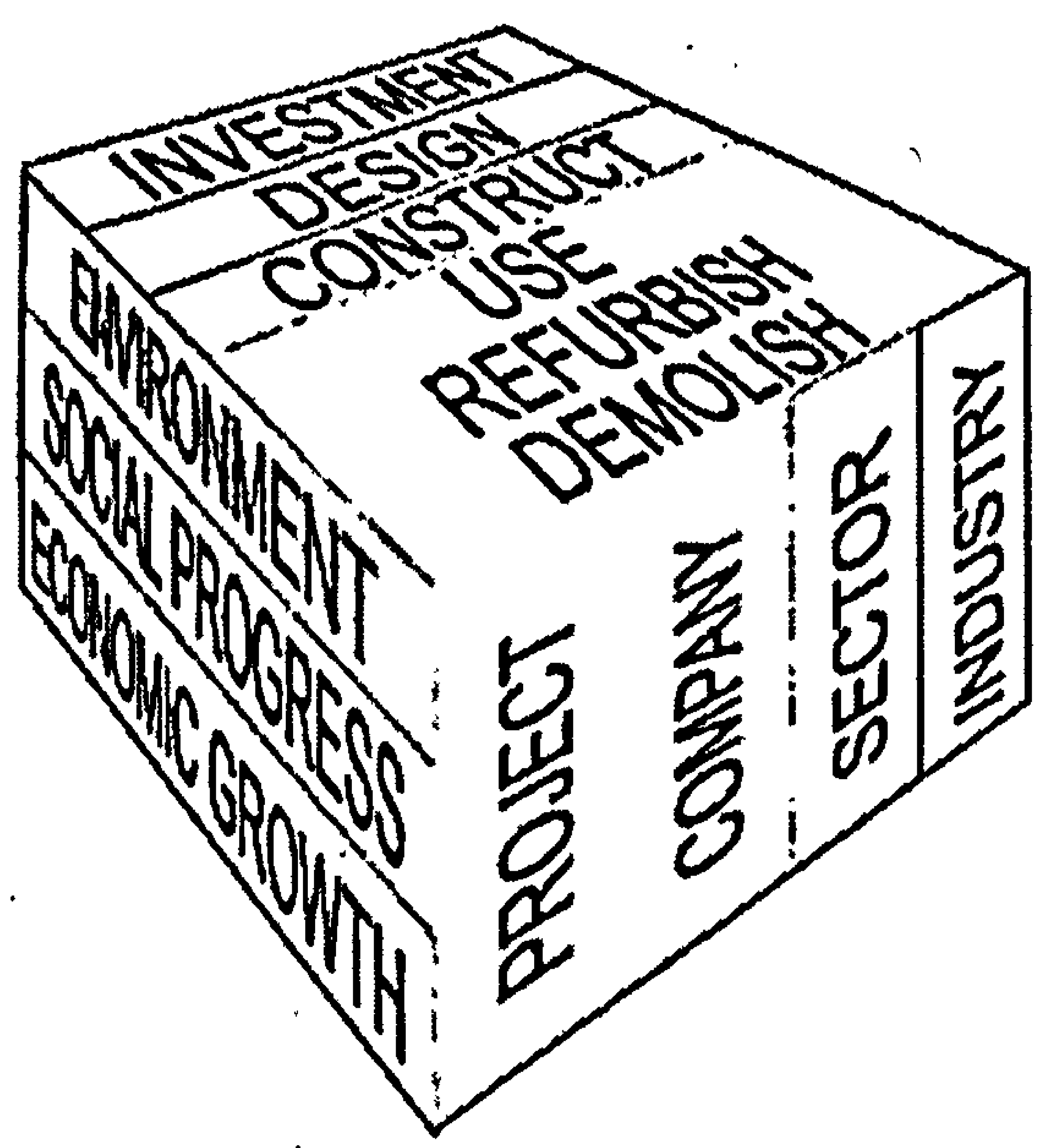


Figure 1.3 Sustainable construction matrix ([15])

1.3.2 Review of UK research on sustainable construction

Research on sustainable construction practice has been executed mainly by sub-sectors, due to the diversity of the construction industry. Figure 1.4 shows the sub-sectors in the construction industry and their main organisations which have contributed to sustainable construction practices.

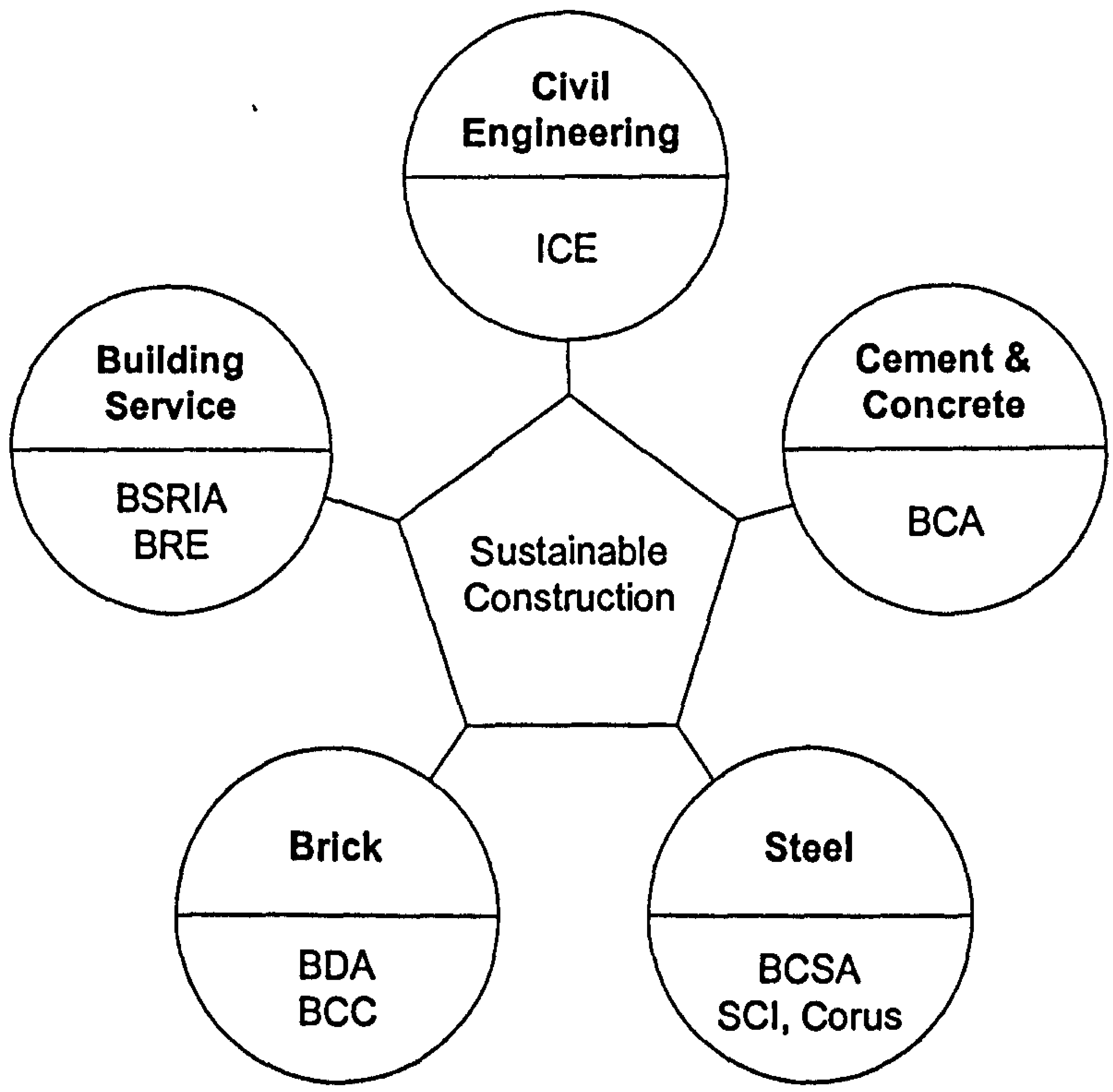


Figure 1.4 Construction industry sub-sectors and their main organisations

1.3.2.1 Civil Engineering

In December 2002, the Institution of Civil Engineers (ICE) council passed a resolution stating, 'Sustainable development is now absolutely central to civil engineering and we must organise ourselves accordingly'. To support and implement this, their sector strategy *Society, Sustainability & Civil Engineering* [4] was published in April 2002, and *the ICE Charter for Sustainable Development* was launched at the ICE Annual Conference in June 2003 [16].

Some research was undertaken to point out the basic directions towards sustainable development in the construction industry [17-20] and to integrate the sustainability strategy across its sector's working practices [21-27]. According to these studies, sustainable construction would be achieved by:

- holistic design for durable structures [18, 21, 24, 25]
- reduction and/or recycling of waste [17, 18, 23]
- use of recycled and alternative materials in aggregates [17, 22-24]
- improved operational efficiency of buildings [21, 23].

1.3.2.2 Cement & Concrete

Cement and concrete production is a complex topic when it comes to sustainability issues, partly because many constituents are involved and partly because sustainable concrete production may be defined in different ways [28]. To address this problem, from around 2001 onwards, many reports have been produced. It is impossible to review all the reports here, but the main issues related to cement and concrete production in terms of sustainability will be reviewed based on work done by the British Cement Association [29-33].

Figure 1.5 shows the statistical data for the proportion of the UK's environmental impact that is attributable to the built environment, construction materials and cement & concrete production. It shows the environmental impacts embodied in the manufacture of cement and concrete are around 2% of the UK totals. In comparison, the operation of buildings and transport account for more than 60% of environmental impacts.

Therefore, the UK cement and concrete sector has not only tried to reduce the environmental impacts from cement and concrete manufacturing itself but also encouraged the use of its products in ways that reduce the environmental impact of buildings and transportation.

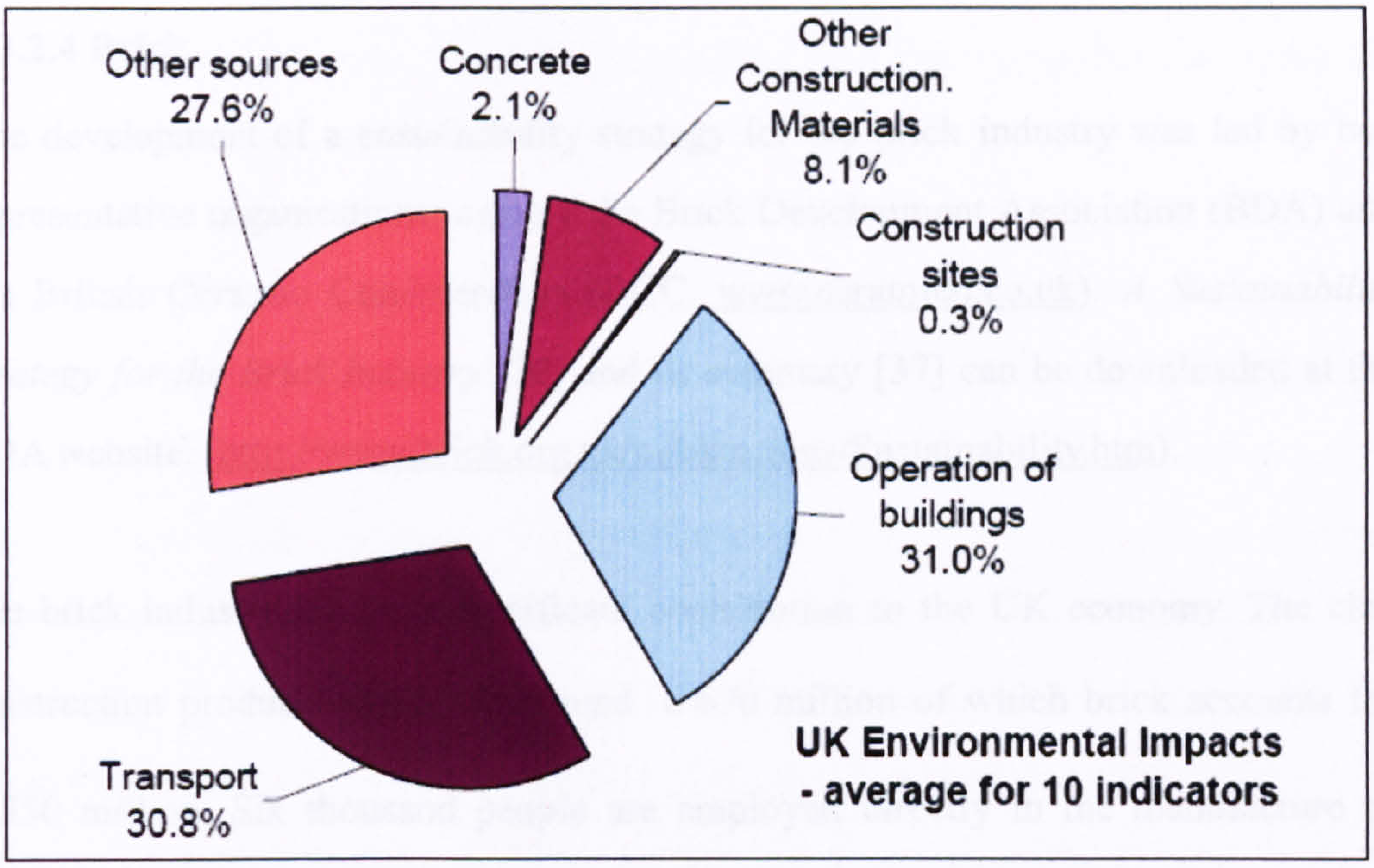


Figure 1.5 Construction related environmental impacts in relation to UK totals. (Indicators are: land use, water use, energy, CO_2, SO_x, NO_x, CO, dust, metals and waste) ([31])

1.3.2.3 Steel

The Steel Construction Sector Sustainability Committee published their strategy, *Sustainable Steel Construction – Building a better future* [34], in 2002. This document was based on the collaborative work of Corus (www.corusgroup.com), the British Constructional Steelwork Association (BCSA, www.steelconstruction.org), the Steel Construction Institute (SCI, www.steel-sci.org) and the University of Sheffield (www. shef.ac.uk).

The strategy emphasizes that the steel construction sector is competitive in terms of sustainability because of their efficiency in construction, low waste, flexibility in modification, high recyclability of steel product, stability in the workplace, and easiness in maintenance, etc. More than anything else, the reuse or recycling of steel components offers greater environmental advantage compared with other construction sectors. In the UK, the recovery rate of steel construction products from demolition sites is 94% with 10% being reused and 84% recycled [35].

1.3.2.4 Brick

The development of a sustainability strategy for the brick industry was led by two representative organisations, namely the Brick Development Association (BDA) and the British Ceramic Confederation (BCC, www.ceramfed.co.uk). *A Sustainability Strategy for the Brick Industry* [36] and its summary [37] can be downloaded at the BDA website. (http://www.brick.org.uk/publications/Sustainability.htm).

The brick industry makes a significant contribution to the UK economy. The clay construction products market is around £670 million of which brick accounts for £550 million. Six thousand people are employed directly in the manufacture of bricks, with many more in the ancillary industries. Brick factories are often located in rural areas, consequently they provide employment in relatively small communities.

The main environmental burden from the brick industry comes from the manufacturing of bricks. Clay extraction has an adverse environmental impact. Brick production requires intensive energy and considerable volumes of water, and generates atmospheric emissions. To reduce or compensate for this, the brick industry has made efforts to restore clay pits and introduce effective regulation and responsible environmental management [36].

1.3.2.5 Building Services

The implementation of sustainability in the building service sector in the UK has mainly been undertaken by the Building Services Research and Information Association (BSRIA) and Building Research Establishment (BRE).

Recognising that sustainable construction could impose a pressure on the building service industry [38], and in order to cope with the UK government's initiative for sustainable construction, the BSRIA brought together representatives from the Building Services industry to develop a sector strategy and promote its implementation [11]. Although the sector strategy for sustainability was not documented, BSRIA has helped the building services companies to meet the sustainability targets. (See www.bsria.co.uk)

BRE is a UK wide organisation which provides consultancy, testing and research services covering all aspects of the built environment. For the systematic application of sustainability to building structures, BRE has collected data and developed a methodology which can choose a best value solution for building structures in terms of sustainability by combining economic and environmental assessment tools [39]. Envest 2, a software program produced by BRE, uses whole life costing and life cycle assessment principles to calculate the cost and environmental impact of a building structure's options, and suggest best solutions according to their trade-off and designer's priorities. (See envestv2.bre.co.uk) Figure 1.6 shows the schematic diagram on which the Envest 2 program is based.

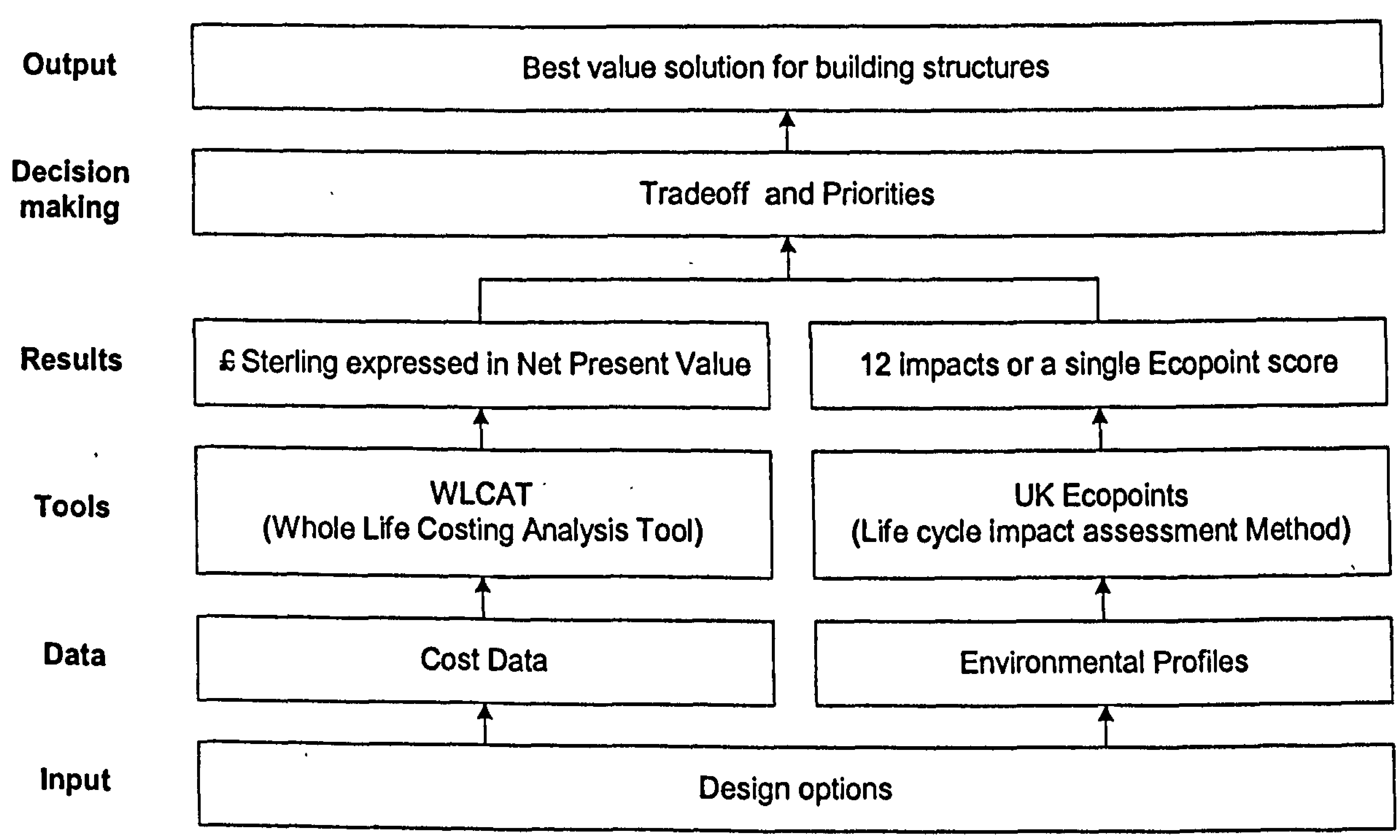


Figure 1.6 The structure of BRE's methodology used in Envest 2 program

In particular, Environmental Profiles [40] and UK Ecopoints [41] are important because the former is the UK specific environmental database for building structures and the latter is the life cycle impact assessment method developed based on the consensus of the UK construction industry. The details for these will be discussed further in Chapter 5.

1.4 The need for sustainable infrastructure management

The management of infrastructure has been a constant and important problem for their owners such as the UK Government and Highways Agency. Generally, it has been acknowledged that good practice of infrastructure management should be adopted to maintain the whole infrastructure within a limited budget. Therefore, as a decision making criteria, economic optimisation has been used in infrastructure management.

In addition to the economic aspect, however, the management of infrastructure can have a great impact on both the environment and also on human life. Therefore, it is desirable to introduce and implement the triple bottom line approach of sustainable development to the decision making for infrastructure management (Figure 1.1).

The special reasons why sustainable infrastructure management is important will be reviewed below. The urgent need for a decision making support tool for sustainable infrastructure management will be emphasised.

1.4.1 The increasing requirement for sustainable management of aging infrastructure

The construction and maintenance of infrastructure such as roads, bridges, tunnels, dams, harbours and buildings is a fundamental and indispensable requirement for the development of society and its welfare.

All the human activities related to infrastructure need money and lead to environmental impacts and social inconveniences. During the whole life cycle of infrastructure, it is generally acknowledged that the construction stage causes the largest economic, environmental and social impacts within a relatively short time period. Most of the input materials are consumed at this stage.

The lifespan of infrastructure spans many decades, even sometimes several hundred years. As time goes on, the fraction of infrastructure which needs maintenance activities keeps increasing. Furthermore, the deterioration rate of infrastructure becomes faster with time, and the demand for maintenance activities is accelerated.

Thus, in developed countries which possess a huge stock of infrastructure whereas the need for new structures is diminished, the management of aging infrastructure consumes more money and produces bigger environmental and social impacts than new construction.

For example, many of the current bridges in the UK have been built from the mid 1950s onwards with the peak time of construction being in the 1970s. The Highways Agency is responsible for approximately 15,000 structures on the trunk road network in England [42]. The huge number of bridge stocks and their continuing deterioration has made the management of infrastructure very complex. Nowadays, the UK government is trying to manage this infrastructure more systematically based on an “asset management” concept. Sustainability principles are at the core of asset management.

From the viewpoint of sustainable development, good practice of infrastructure management is the most effective way to reduce the economic, environmental and social impacts through the whole life cycle of the structure. The optimised maintenance activities of infrastructure should make it possible to extend the life of infrastructure with a small amount of financial and material resources, and delay the demolition and/or reconstruction timing.

1.4.2 Special factors to be considered in sustainable infrastructure management

Although it is generally admitted that the good practice of infrastructure management is useful in terms of sustainability, it is not so simple to choose the most sustainable infrastructure management practice. This is because the decision making for infrastructure management should be based on many factors such as the understanding of the infrastructure's deterioration mechanism, the effectiveness of selected maintenance activities to extend the life of the structure, and additional impacts from linked events such as traffic disruption, etc.

The understanding of infrastructure's deterioration mechanism is essential for planning of future maintenance activities. The deterioration mechanism changes depending on the structure type, initial construction condition, the severity of the surrounding environment, etc. All these factors are complex and contain uncertainties. The modelling of this complex and uncertain deterioration mechanism of the structure is the prerequisite for sustainable infrastructure management.

Another difficulty in infrastructure management is the variety of maintenance options. Infrastructure management is made up of a series of maintenance activities. The maintenance activities can be classified as routine, preventative and essential, according to the purpose and application timing. It is now accepted that successful management relies on combining these activities. Furthermore, the materials used for maintenance activities are so diverse from the basic materials like concrete, steel and brick, and include numerous chemical and sometimes electrochemical products. For sustainable infrastructure management, a deep knowledge of maintenance options and their consequences is required.

Lastly, often additional impacts from accompanying events should be considered. Traffic disruption is the most obvious issue. In the UK, when the maintenance option of bridge structure is chosen, the impacts from traffic disruption should be taken into account. The calculation of traffic delay cost and environmental impacts from traffic disruption is a complex and highly uncertain process and renders the identification of optimum maintenance options more difficult and subject to additional assumptions.

In conclusion, the achievement of sustainability in infrastructure management requires a totally different approach from other construction cycles. So far research on sustainable construction concentrated mainly on design, materials production and construction practices. Therefore, at the outset of this study it was considered useful to develop a systematic methodology on how to achieve sustainable infrastructure management.

However, it is impossible to develop and implement a single methodology for all infrastructure types, because of their own specific characteristics. The modelling of different characteristics results in a different deterioration model, key performance indicators, and decision making tools.

Bearing this in mind, this study concentrates on bridge structures, as one of the representative and critical elements of infrastructure networks, and focuses on the development of a decision support tool which will help in finding suitable bridge maintenance options in terms of sustainability. It is considered that the suggested methodology for sustainable bridge maintenance can be adapted to other infrastructure types but would of course require additional work for specific implementation.

1.5 Organisation of thesis

The overall decision making framework for the present research is explained in Chapter 2. In other words, the basic assumptions for decision making are addressed, and the decision making components such as objectives, options, criteria, analytical tools and MCDA techniques are defined/chosen following the general decision making process. Additionally, the necessity of uncertainty analysis is emphasized.

In Chapter 3, the methodology for developing alternative bridge maintenance plans is described. For this, the corrosion mechanism due to chloride attack and carbonation is briefly reviewed and the types of maintenance options are classified. Then, the characteristics of maintenance options for water control, concrete and steel bridges are explained. Furthermore, the methods to develop maintenance plans by combining maintenance options based on time and/or performance based approaches are described.

In Chapter 4, the way to calculate economic aspect of bridge maintenance activities, i.e. maintenance costs, are addressed. In other words, the principles of whole life costing (WLC) and its application to alternative maintenance plans are explained. More specifically, direct costs and traffic delay costs due to maintenance activities are quantified and combined.

In Chapter 5, the environmental aspect, i.e. environmental impacts, related to bridge maintenance activities are quantified. For this, the generals of life cycle assessment (LCA) tool are reviewed and they are applied to calculate direct environmental impacts of four maintenance options for concrete bridge as well as indirect environmental impacts from additional fuel consumption due to traffic disruption.

In Chapter 6, a quantitative methodology which combines the development of maintenance plans, WLC, LCA and uncertainty analysis, which were explained in chapters 2 to 5, are developed. For this, a computer program has been developed using 'FORTRAN' programming language. The characteristics/functions of deterministic and probabilistic analyses included in the developed program and their corresponding input file structure are explained.

In Chapter 7, a series of case studies are undertaken in order to verify the validity of the proposed methodology and the developed program. For this, an example is chosen and deterministic as well as probabilistic analyses are executed.

Chapter 8 summarises the achievements of the present research study. In addition, suggestions were made for further work.

Chapter 2

Development of a decision making framework for sustainable bridge maintenance

2.1 The decision making process

As explained in Chapter 1, the main concern of this study is to develop a decision making support tool which will help in finding preferable bridge maintenance options/plans in terms of sustainability. As a first step, this chapter will develop a decision making framework for so-called sustainable bridge maintenance. This aim can be achieved by understanding the general decision making process and applying it carefully to a given situation. Therefore, this chapter starts with a brief description of a decision making process.

Decision making is required when multiple options (or alternatives) exist in order to reach same objectives. Generally, single or multiple criteria (or indicators) are used to compare the options. As the number of criteria increases, the decision making becomes a comprehensive complex process. Additional data collection and processing is required. Therefore, the number of criteria used in decision making should be carefully determined to satisfy, on one hand, the comprehensiveness of decision making and, on the other, the ease of analysis and available possibilities of data collection.

After the criteria are selected, the options are analysed or evaluated. If a single criterion is used, the decision making is straightforward. Usually, an option which has the nearest value from a target value becomes optimal. On the other hand, if multiple criteria are used, multi criteria decision aid/analysis (MCDA) techniques are required. The choice of a MCDA technique depends on the number of options, the number of criteria and the purpose of decision making, etc. By applying an appropriate MCDA technique, an optimal option can be selected.

In short, the general decision making process is made up of following steps [43].

- Identifying objectives
- Identifying options for achieving the objectives
- Identifying the criteria to be used to compare the options
- Analysis of the options
- Making choices

Based on the above decision making process, a decision making framework for sustainable bridge maintenance will be developed.

2.2 Decision making process for sustainable bridge maintenance

2.2.1 Basic assumptions

In an ideal situation, decision making is undertaken on a fully quantitative basis with no uncertainty. In reality, most of the decision making situations are affected by non-quantitative or irrational factors such as the decision maker's personal characteristics, stakeholders' distorting pressures, and institutional mechanisms used to generate the alternatives and solve any given problem [44]. In order to reach an objective and well structured decision making process, these factors should be taken into account by either choosing a more relevant qualitative framework or introducing some reasonable assumptions.

Bearing this in mind, several questions regarding the fundamental objective of decision making, the identity of stakeholders and decision makers, and the level of decision making will be addressed here in order to clarify the boundary of the developed decision making framework.

1) What is the fundamental objective of decision making?

Decision making in relation to bridge maintenance could have many facets, but ultimately aims to select proper maintenance activities. Bridge maintenance activities are generally categorised into routine, preventative and essential. Among them, routine maintenance activities are ordinary and simple, and they are executed independently of the decision maker's preferences. Therefore, a decision making framework for bridge maintenance should mainly deal with preventative and essential maintenance activities. In other words, the fundamental objective of decision making in bridge maintenance is the optimised selection of preventative and/or essential maintenance activities and their application timing.

2) Who are the stakeholders and who is the decision maker?

The representative stakeholders related to bridge maintenance activities are bridge owners, maintaining agents and bridge users. The relationship between them is shown in Figure 2.1

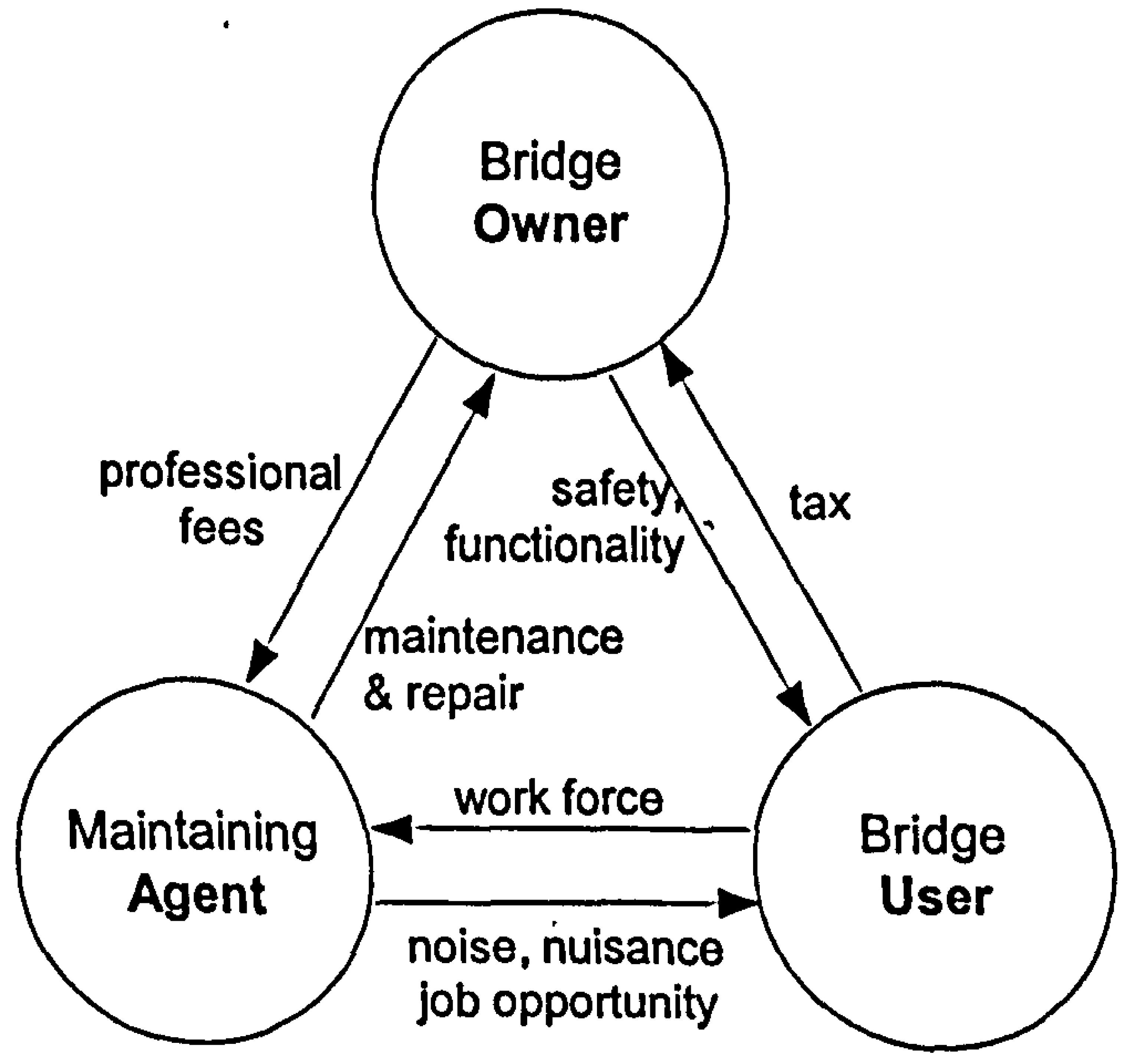


Figure 2.1 Relationships between stakeholders in bridge maintenance.

The bridge maintenance activities are executed through mutual relations among the bridge owners, maintaining agents and users. Bridge users and maintaining agents can take part in the decision making process indirectly by expressing their opinions or complaints, but usually they are not in a position to impose their preferences and objectives. Therefore, in this study, it is assumed that the decision maker for bridge maintenance is the bridge owner.

More specifically, in the UK, the officers or staff who are responsible for bridge maintenance in central government, local government and the Highways Agency form the body of decision maker(s) for bridge maintenance. In addition, it may be assumed groups of bridges owned by private companies (e.g. Network Rail) would also be managed in a similar manner due to the safeguards put in place through legislation, regulatory bodies, etc. However, in the case of railway bridges it might be easier to combine so-called "direct" and "indirect" costs of bridge maintenance since the latter can be translated into penalties paid by the owner (Network Rail) to the train operating companies (franchise holders).

3) What is the level of decision making?

Decision making related to bridge maintenance can be broadly undertaken at two levels: project level and network level. Decision making at project level treats a single bridge structure or its components. On the other hand, network level considers a large number of bridge structures at the same time, and attempts to prioritise, and rationalise the execution of, their maintenance activities. Clearly, decision making at network level requires data relevant to all the structures considered which could lead to more complex decision making process.

Comparing the two levels, decision making at project level is a basic and fundamental requirement for bridge maintenance, and it could be argued that decision making at network level can be reached by aggregating project level decisions. This study concentrates on decision making at project level, thus focusing on finding optimum maintenance plans for single bridge structures.

2.2.2 Identifying objectives

A traditional objective in infrastructure management is to minimise cost input on the condition that the safety or reliability value of the structure is above a critical or target level. This approach concentrates on economic aspects and the whole life costing technique has been used as a main analytical tool [45].

However, sustainable development objectives include optimisation of environmental and social aspects. For example, this means that environmental pollution and local nuisance from bridge maintenance activities should be minimised at the same time.

Therefore, the objectives of sustainable infrastructure management can be stated as identifying/applying maintenance plans and taking actions which minimise cost, environmental impact and local nuisance over the service life of the structure whilst maintaining a safety or reliability indicator above an acceptable/tolerable level.

2.2.3 Identifying options for achieving the objectives

The maintenance options available for achieving "sustainable" bridge maintenance are the same as those considered in "traditional" bridge maintenance. Maintenance plans can be generated by considering different maintenance options such as concrete repair, waterproofing, and rehabilitation, etc. and their combination. Different maintenance options vary in respect of required time and materials, have different cost, and produce different improving effects in safety/reliability and durability. Hence, maintenance plans can be generated diversely by combining different maintenance options, and different maintenance plans will result in different economic, environmental and social impacts.

Basically, three approaches can be used in the determination of maintenance plans. They are:

(a) time-based approach: applicable primarily to preventative maintenance actions;
(b) performance-based approach: applicable primarily to essential maintenance actions;

(c) time- and performance-based approach: applicable to both preventative & essential maintenance actions.

The time-based approach uses two variables: time of first application and time of subsequent applications, independently of predicted or measured profiles of any performance indicators. In the case of a performance-based approach, maintenance actions are applied when a performance threshold is violated, which implies that some prediction/estimation of performance is needed. Time- and performance-based approach is a mix of these two approaches. Typically, the timing of preventative maintenance actions may be determined by a time-based approach but, in addition, essential maintenance is applied if/when some performance threshold is violated.

Specific maintenance plan generation methods related to the above approaches will be discussed in more detail in Chapter 3.

2.2.4 Identifying criteria to be used in comparing options

In order to compare the sustainability performance of developed bridge maintenance plans a set of criteria or indicators are needed. The efforts for the development of performance indicators for sustainable construction in the UK were already reviewed in 1.3.1. However, project level indicators for 'use' stage were not developed well. Therefore, it is necessary to determine a group of indicators to quantify the sustainability performance of bridge maintenance plans.

For this, it may be useful to refer to the general project level indicators used in other life cycles for sustainable construction. Table 2.1 shows some examples of operational indicators extracted from the CIRIA report, *Sustainable construction – company indicators* [15], to measure the sustainability of the construction activities with regard to ten key construction themes.

Normally, economic and environmental performance can be represented by cost and the quantities of used energy and/or emission, etc., respectively. On this basis, it is relatively straightforward to quantify and calculate economic and environmental performance.

Table 2.1 Ten key construction themes and their operational indicators (from [15])

Key themes	Operational indicators
Environmental indicators	
Avoiding pollution	- SO_2, PM10 and NO_x released (in tonnes) per £ turnover arising from construction activities - Average distance travelled per tonne of materials from suppliers to site - Number of complaints received per project site for noise and dust - Proportion of construction costs on nuisance mitigation - Tonnes of wastes arising to landfill per £ turnover - Tonnes of hazardous wastes arising per £ turnover
Protecting and enhancing bio-diversity	- Percentage of project sites for which appropriate mitigation measures have been implemented to protect sensitive ecosystems
Efficient use of resources	- Tonnes of unused construction materials disposed to landfill - Percentage of recycled and secondary aggregate used in construction - Water consumption in (m^3) per £ turnover arising from construction site activities
Improved energy efficiency	- CO_2 released (in tonnes) per £ turnover arising from construction activities
Social indicators	
Respect for staff	- Percentage of staff receiving formal annual appraisals - Percentage of staff undertaking structured training programmes including social and environmental aspects of construction - Proportion of staff from ethnic minorities - Percentage of staff involved in ongoing surveys of job satisfaction
Working with local communities	- Number of complaints received about inappropriate behaviour from employees working on site
Partnership working	- Number of clients (suppliers) with whom long-term strategic alliances have been formally agreed
Economic indicators	
Improved project delivery	- Average actual duration (cost) at Commit to Construct less the estimated duration (cost) at Commit to Invest, expressed as a percentage of the latter
Increased profitability and productivity	- Average normalised construction cost of a project less the normalised cost of a similar project in 1999, expressed as a percentage of the latter

On the other hand, it is difficult to quantify the social criteria influenced by bridge maintenance activities. Social criteria in this context may include different indicators of noise, nuisance, inconvenience and job opportunity, etc for different maintenance activities (See Figure 2.1). More than anything else, there are no objective tools to measure these indicators. A single activity/task may have both a positive and a negative impact, depending upon the individual perspective (e.g. noise vs. job opportunity). Furthermore, individuals may change their mind over time [46]. In view of this, it is currently practically impossible to formulate a social impact score for bridge maintenance activities. Therefore, social impacts arising from bridge maintenance activities are not considered in this study, and only economic and environmental factors are calculated and integrated.

2.2.5 Analysis of options

As previously mentioned, in this study the performance indicators for sustainable bridge maintenance are confined to economic and environmental factors. Various methodologies exist for evaluating economic and environmental performance. Therefore, it is necessary to select appropriate methodologies for respective criteria. These should be both systematic/rigorous and reasonable/practical.

Figure 2.2 shows the framework for environmental decision making [47]. The framework shown makes a distinction between concepts and tools. Concepts broadly comprise the approaches leading to environmental sustainability, such as life cycle thinking, design for the environment, and cleaner technology. Tools, on the other hand, are operational methods supporting the concepts. Tools can be categorised according to their focus as analytical tools and procedural tools. Analytical tools involve: modelling the system in a quantitative or qualitative way in order to provide technical information for a better informed decision, while procedural tools focus on procedures which pave the way for an environmentally based decision process. The focus of quantitative analytical tools is on computational algorithms which require quantitative data. Qualitative analytical tools may use both qualitative and quantitative data. All types of tools are supported by technical elements, and the technical elements are supported by data.

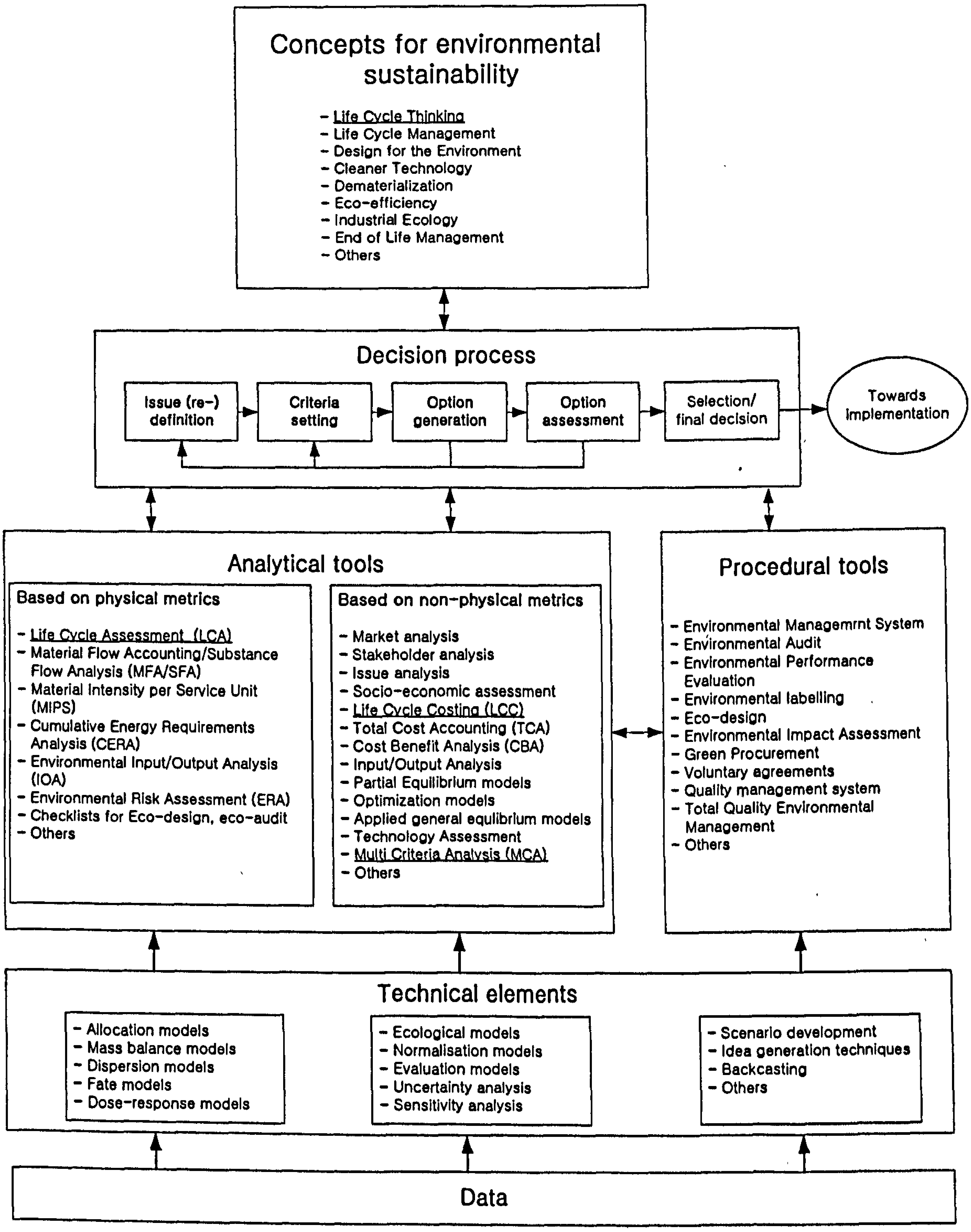


Figure 2.2 Decision making framework based on environmental information

The most representative concept for building or bridge management is life cycle thinking. Life cycle thinking considers the 'cradle-to-grave' implications of any action. A bridge is a long life structure, so it is generally accepted that life cycle thinking is suitable for underpinning the sustainability of construction and life-cycle management.

Analytical tools for environmental and economic performance based on life cycle thinking include Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), respectively. In the UK bridge management community, the term of Whole Life Costing (WLC) is often used instead of Life Cycle Costing. Herein, Whole Life Costing is adopted for the methodology associated with evaluating the economic performance indicators of bridge maintenance actions. On the other hand, Life Cycle Assessment (LCA) is used for evaluating environmental performance indicators. These tools will be described in more detail in Chapter 4 and 5, respectively.

2.2.6 Making choices

2.2.6.1 The integration of Whole Life Costing and Life Cycle Assessment

An analytical tool may support a decision process as stand alone or in combination with other tools and criteria. In this study, two analytical tools, namely Whole Life Costing and Life Cycle Assessment, are chosen to quantify the economic and environmental aspects of bridge maintenance plans. Consequently, the question of how to combine or integrate these two aspects becomes important. To answer this question, the past research on the integration of WLC and LCA results will be reviewed in the following and the most suitable approach for this study will be selected.

Previous approaches for the integration of WLC and LCA results can be categorised into three groups. The first approach is to calculate overall performance scores of alternatives from WLC and LCA results, and use these overall scores to identify the most preferable alternative. Representative examples are found in the BEES program [48] and the Econo-Environmental Return index [49].

The BEES (Building for Environmental and Economic Sustainability) program is a software tool developed in the U.S. to select cost effective, "green" building products [48]. BEES measures the environmental and economic performance of building products using the life-cycle assessment approach, and combines them into an overall performance measure using Multi-attribute Decision Analysis. Overall performance scores are calculated by the formula below [50] and the alternative with the smallest overall score is reflected as the best option.

$$S_j = \left[(w_{en} * \frac{ES_j}{\sum_{j=1}^{n} ES_j}) + (w_{ec} * \frac{LCC_j}{\sum_{j=1}^{n} LCC_j}) \right] * 100 \text{, where} \qquad (2.1)$$

S_j = overall performance score for alternative j;

w_{en}, w_{ec} = environmental and economic performance weights, respectively

($w_{en} + w_{ec} = 1$);

n = number of alternatives;

ES_j = environmental performance score for building product alternative j;

LCC_j = total life-cycle cost in present value dollars for alternative j;

The *Econo-Environmental Return* (*EER*) suggested by Gontran F. Bage is another overall index which combines economic and environmental assessment results [49]. The EER formula (Eq. 2.2) was derived based on the economic concept of "Return on Investment". An alternative which has the highest EER value can be considered as the best compromise between the economic and the environmental aspects. However, this formula assumes that the weighting factors for economic and environmental aspects are the same, so if the decision maker wants to apply different priorities, this EER formula must be modified.

$$EER = \frac{(EnvI^{+} \cdot EconI^{+}) - (EnvI^{-} \cdot EconI^{-})}{(EnvI^{-} \cdot EconI^{-})} \text{, where} \qquad (2.2)$$

$EnvI^{+}$: the positive environmental impacts (the environmental credits or benefits resulting from a recycling loop)

$EnvI^{-}$: the negative environmental impacts (usually called the environmental impacts)

$EconI^{+}$: the positive economic aspects (benefits)

$EconI^{-}$: the negative economic aspects (costs)

The second approach for integrating economic and environmental assessment results is just to show the cost and environmental performance score together without calculating overall index. This approach was used in the BRE methodology for sustainable building designs in the UK [39] and in the PTLaser program developed in the U.S. for general process modeling [51]. Also, Itoh calculated CO_2 emission and life-cycle cost separately in order to compare the life cycle performance of two bridge types [52], and Bovea used the environmental score, cost and customer valuation together as a driver in order to increase the product value during design [53]. The limitation of this approach is that the decision making could be direct only when both the cost and environmental performance score of one alternative are superior to all other alternatives. For other cases, multi-criteria decision analysis principle should be introduced for final decision making.

The third approach is to use LCA outcomes as an input to WLC. In other words, this approach tries to quantify environmental impacts in monetary terms and add them to other costs. Examples for this approach can be found in TCAce tool [51], LCECA model suggested by Senthil [54], and environmental LCC in Reich's research [55]. In TCAce tool, an abbreviated term for 'Total Cost Assessment', the environmental costs are considered as an 'external cost' or 'society cost' to expand the decision scope to include environmental factors [51]. Here, external costs mean costs for which the company is not responsible at a specific time, in the sense that there is no market or governmental regulation that assigns them to the company [53]. Senthil [54] developed LCECA (Life Cycle Environmental Cost Analysis) model to include the eco-costs into the total cost of a product. In this model, eco-costs include cost of effluent/waste control, cost of waste treatment, cost of waste disposal, cost of environmental management systems, cost of eco-taxes, cost of rehabilitation, cost of energy, and cost savings of recycling and reuse strategies. Reich [55] used three different environmental LCC techniques, i.e. ECON '95, EcoTax '99 and EPS 2000, to monetarise environmental effects such as emissions and resource use in economic assessment of municipal waste management systems. The above examples show some possibilities of estimating environmental costs. However, this approach can be controversial because it is impossible to monetarise properly all environmental impacts.

Another possible approach to integrate WLC and LCA is to add cost flows into the traditional LCA framework [51]. However, it is difficult to treat cost flows just like physical flows, and no example which has used this approach has been found.

Recently, the integration of WLC and LCA is an emerging issue especially within the SETAC LCC working group [56-58] (see www.setac.org) and EU project DANTES (see www.dantes.info). However, there has been no agreed general tool which integrates WLC and LCA results. Therefore, an appropriate integration method should be selected for any given decision making situation. When the characteristics and limitations shown in the above approaches are considered, the BEES program's approach which uses multi-attribute decision analysis technique is considered to be the most comprehensive and reasonable. Keeping this in mind, this study will review the characteristics of general multi-criteria decision analysis/aid (MCDA) techniques and select the most suitable MCDA technique for this study.

2.2.6.2 General principles of Multi-Criteria Decision Analysis/Aid techniques

Generally, Multi-Criteria Decision Analysis/Aid (MCDA) is an analytical tool which facilitates the combination of different types of outcome in decision making. It assists the decision maker in identifying trade-offs between different criteria and finding the 'best option'. There are a large number of MCDA techniques, and no single technique is superior to all others or suitable for all decision making situations. Therefore, it is important to choose and apply a proper MCDA tool for a given decision making situation.

MCDA methods can be sub-divided into as *discrete* and *continuous*. Discrete MCDA methods are applied to problems where a decision maker is choosing or ranking a *finite number of alternatives* which are measured by *two or more relevant criteria*. In other words, discrete MCDA problems involve analysis of a finite and generally small set of discrete and predetermined options or alternatives. On the other hand continuous MCDA problems involve the *design* of a "best" alternative by considering the trade-offs within a set of interacting design constraints. In continuous MCDA problems, the number of alternatives is effectively infinite, and the trade-offs among design criteria are typically described by continuous functions [59]. The trade-offs between economic and environmental criteria in bridge maintenance correspond to discrete MCDA problems, due to the nature of bridge maintenance plans.

According to Roy [60], most of the discrete MCDA methods fall within the following three categories:

1) single-criterion synthesis approach, where incomparability is excluded;
2) outranking synthesis approach, where incomparability is accepted;
3) interactive local judgement with trial and error iterations.

Each approach includes various MCDA techniques, and each MCDA technique is based on complex logic and mathematical relationships. Therefore, the detailed description of all MCDA techniques is beyond this study's scope. Instead, this study is based on Guitouni's and Martel's summary of some representative MCDA techniques shown in Table 2.2.

Table 2.2 Comprehensive list of some known MCDA methods (Adapted from [61])

MCDA	Description of the MCDA
Elementary methods	
Weighted sum	The global performance of an alternative is computed as the weighted sum of its evaluations along each criterion. The global performance is used to make a choice among all the alternatives.
Lexicographic method	Based on the logic that in some decision making situation a single criterion seems to predominate. The procedure consists in comparing all the alternatives with respect to the important criterion, and proceeds with the next one until only one alternative is left.
Conjunctive method	An alternative which does not meet the minimal acceptable level for all criteria is rejected. The minimal acceptable levels for each criterion are used to screen out unacceptable alternatives.
Disjunctive method	An alternative is selected on the basis of its extreme score on any one criterion. Desirable levels for each attribute are used to select alternatives which equal or exceed those levels on any criterion.
Maximin method	The overall performance of an alternative is determined by its weakest or poorest evaluation
Single synthesizing criterion	
TOPSIS (technique for order by similarity to ideal solution)	The chosen alternative should have the profile which is the nearest (distance) to the ideal solution and farthest from the negative-ideal solution
MAVT (multi-attribute value theory)	Aggregation of the values obtained by assessing partial value functions on each criterion to establish a global value function V. Under some conditions, such V can be obtained in an additive, multiplicative or mixed manner.
UTA (utility theory additive)	Estimate the value functions on each criterion using ordinal regression. The global value function is obtained in an additive manner.
SMART (simple multi-attribute rating technique)	Simple way to implement the multi-attribute utility theory by using the weighted linear averages, which give an extremely close approximation to utility functions. There are many improvements like SMARTS.
MAUT (multi-attribute utility theory)	Aggregation of the values obtained by assessing partial utility functions on each criterion to establish a global utility function U. Under some conditions, U can be obtained in an additive, multiplicative or distributional manner
AHP (analytic hierarchy process)	Converting subjective assessments of relative importance into a set of weights. This technique applies the decomposition, the comparative judgments on comparative elements and measures of relative importance through pairwise comparison matrices which are recombined into an overall rating of alternatives.
EVAMIX	Two dominance indexes are calculated: one for ordinal evaluations and the other one for cardinal evaluations. The combination of these two indexes leads to a measure of the dominance between each pair of alternatives.

Fuzzy weighted sum	These procedures use α-cut technique. The α level sets are used to derive fuzzy utilities based on the simple additive weighted method.
Fuzzy maximin	This procedure is based on the same principle as the standard maximin procedure. The evaluations of the alternatives are fuzzy numbers.
Outranking methods	
ELECTRE I	The concept of outranking relationship is used. The procedure seeks to reduce the size of nondominated set of alternatives. The idea is that an alternative can be eliminated if it is dominated by other alternatives to a specific degree. The procedure is the first one to seek to aggregate the preferences instead of the performances. There are many improvements like ELECTRE IS, ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE TRI.
PROMETHEE I	PROMETHEE I is based on the same principles as ELECTRE and introduces six function to describe the decision maker preferences along each criterion. This procedure provides a partial order of the alternatives using entering and leaving flows.
PROMETHEE II	PROMETHEE II is based on the same principles as PROMETHEE I. This procedure provides a total preorder of the alternatives using an aggregation of the entering and leaving flows.
MELCHIOR	This is an extension of ELECTRE IV
ORESTE	This procedure needs only ordinal evaluations of the alternatives and the ranking of the criteria in term of importance
REGIME	A pairwise comparison matrix is built using +1 if there is dominance, 0 if the two alternatives are equivalent and -1 for the negative-dominance. The aggregation of these weighed scores provides a total preorder of the alternatives
NAIADE (novel approach to imprecise assessment and decision environments)	This procedure uses distance semantics operators to assess the pairwise comparisons among alternatives. The fuzzy evaluation are transformed in probability distributions and as PROMETHEE, this procedure computes entering and leaving flows
Mixed methods	
QUALIFLEX	This procedure uses successive mutations to provide ranking of the alternative corroborated with the ordinal information
Fuzzy conjunctive/ disjunctive method	When data are fuzzy, the match between values and standard levels provided by the decision maker and the evaluations becomes vague and a matter of degree. The degree of matching is computed using the possibility measure and the necessity measure. The alternatives with the highest degree of matching are considered the best
Martel and Zaras method	This procedure uses the stochastic dominance to make pairwise comparisons. These comparisons are used as partial preferences and an outranking relation is built based on a concordance index and discordance index

Among the MCDA techniques, the multi-attribute utility theory (MAUT) and the multi-attribute value theory (MAVT) are major methods within the single synthesizing criterion approach. These methods assume that there exists a utility (or a value) function U to represent the decision maker's preferences. In this manner, the analyst's task consists of the assessment of such a function and hence the ranking of the alternatives is straightforward. SMART and UTA are simplified methods based on MAUT principle.

The ELECTRE method was the first one that used an outranking synthesizing approach. Other methods like different ELECTRE, PROMETHEE methods, ORESTE, REGIME and MELCHIOR are based on the same concept as ELECTRE, but used different preference structures.

Based on the understanding of MCDA techniques, the most suitable MCDA methods for this study will be selected and the reasons will be explained below.

2.2.6.3 The application of MCDA techniques to this study

The basic assumption in choosing MCDA techniques in this study is that the relative importance between economic and environmental criteria cannot be predefined and their relative importance should be judged/determined by a decision maker who is responsible for bridge maintenance. For example, if lexicographic method in above Table 2.2 is applied, it may be possible that some maintenance plans which have even minimum value of cost or environmental score are not chosen as optimal. Therefore, this study will use formal optimisation techniques.

Assuming that total life cycle costs and environmental impacts for one maintenance plan can be expressed by a single cost value and a single environmental score, respectively, then the economic and environmental impact from each maintenance plan can be represented as a single point in a two-dimensional Cartesian space whose two axes represent cost and environmental score. Thus, a schematic graph as shown in Figure 2.3, whose points represent the cost and environmental score for all feasible bridge maintenance plans, can be obtained. In order to find the most preferable option from this intermediate result, the principles of MCDA techniques can be used.

The MCDA techniques applied in this study are based on the principle of 'outranking method' and 'SMART' method. Briefly, the principle of outranking method is used to screen out the 'dominated' options and then 'SMART' method is used for the selection of the most preferable 'best option' from several potential best options.

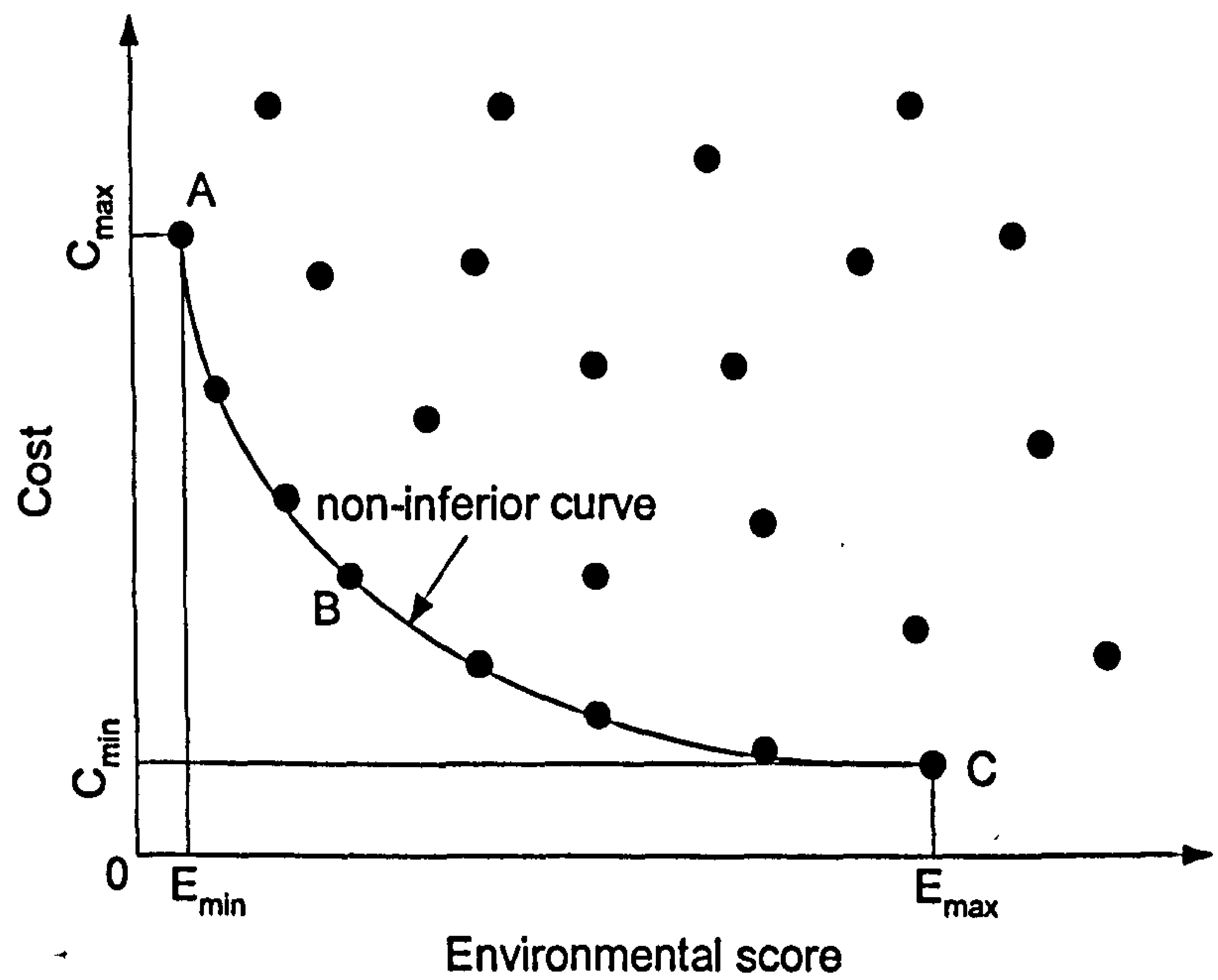


Figure 2.3 Two-dimensional graph representing economic and environmental impact of all feasible bridge maintenance plans.

Firstly, the principle of 'outranking method' is used to screen out or eliminate the 'dominated' alternatives. The outranking method is based on pairwise comparison, and the application to this study is as follows. If both the cost and environmental score of one option are larger than those of another option, then the former option is considered to be dominated by the latter option and it can be screened out in any further search for the best maintenance plan. Through the systematic application of outranking principle, all the dominated options can be screened out, and several dominating options, i.e. the points on the non-inferior curve shown in Figure 2.3, can be identified. The points on the non-inferior curve comprise the potential best maintenance plans. This method is also known as 'Pareto analysis' or 'Pareto principle' and is widely used in multi-objective optimisation, for example see [62].

Secondly, the 'SMART' method can be introduced to choose the most preferable option among the several potential best maintenance plans. Each maintenance plan chosen by the 'outranking principle' could become a best maintenance plan depending on the decision maker's preference. In order to quantify the total preference, it is necessary to normalise cost and environmental score and introduce weighting factors for both values. There are several ways to normalise different parameters such as cost and environmental score. The basic approach is to divide them by their maximum value or by a summation index. For example, the BEES program divides cost and environmental score by their overall sum from all considered alternatives (Eq. 2.1). However, it is not clear whether the normalised value i.e. divided by maximum or sum represents the total preference properly. If the normalised cost and the environmental score have different ranges of values, then the same weighting factors given for cost and environmental score may have different meaning in calculating the total preference. In order to avoid this problem, in this study the 'SMART' method is adopted as a tool for normalising and integrating the cost and environmental score.

The main stages in the 'SMART' method are given below [63]. Here, 'attributes' are equivalent to 'criteria' used in this study.

Stage 1: Identify the decision maker (or decision makers).

Stage 2: Identify the alternative courses of action.

Stage 3: Identify the attributes which are relevant to the decision problem.

Stage 4: For each attribute, assign values to measure the performance of the alternatives on that attribute.

Stage 5: Determine a weight for each attribute.

Stage 6: For each alternative, take a weighted average of the values assigned to that alternative.

Stage 7: Make a provisional decision.

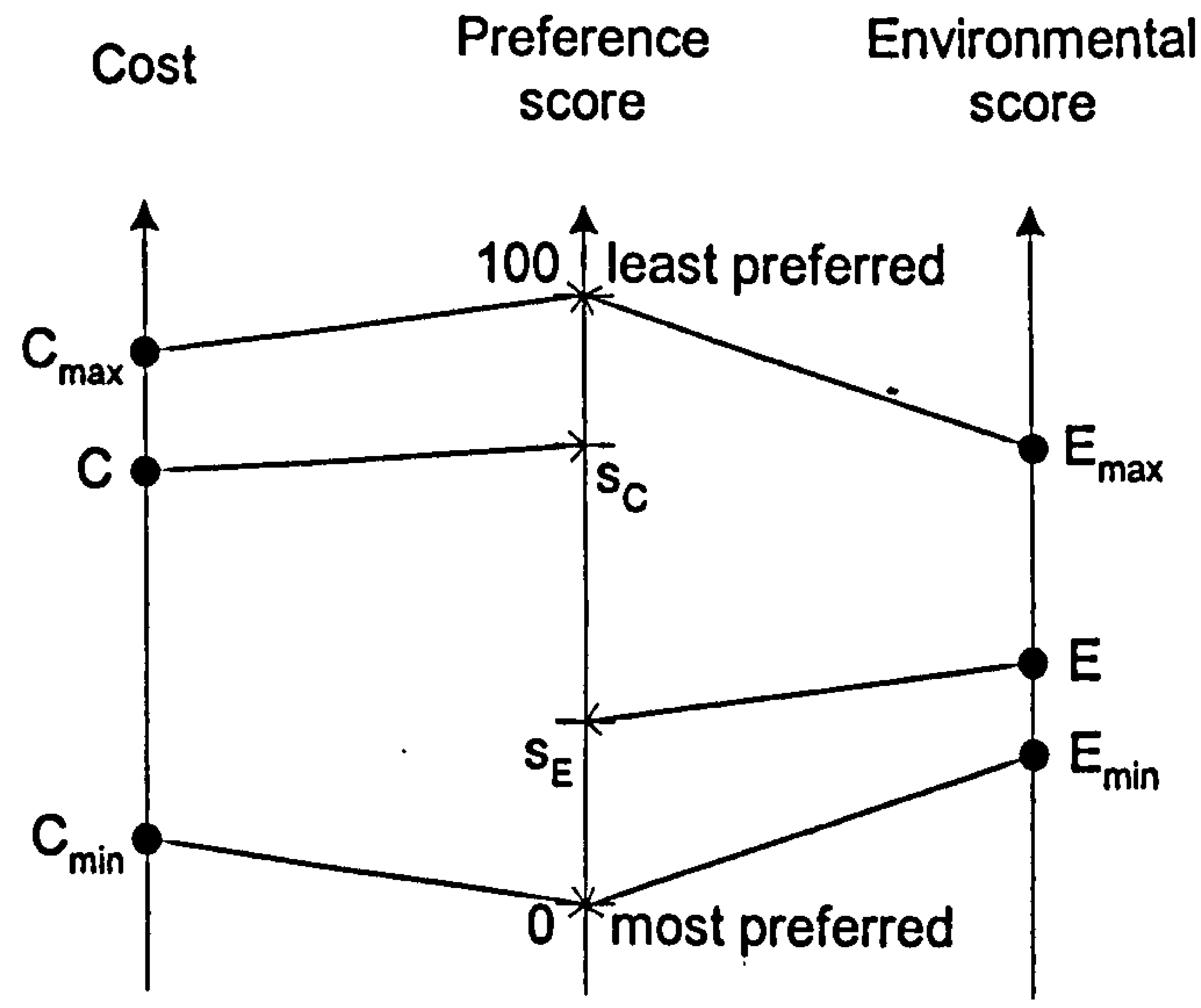
Stage 8: Perform sensitivity analysis.

Stages 1 to 3 have already been executed in this study, and stages 4 to 6 should be implemented in order to reach a decision. The core concepts used in stages 4, 5, and 6 are relative strength of preference, swing weighting and additive modelling, respectively. The details of stages 4, 5 and 6 are described below.

In 'SMART' analysis, the measured or calculated values, e.g. cost and environmental score in this study, are transformed so that the transformed values of all criteria are on the same scale, normally 0 to 100. Usually, on each criterion, the most preferable value is transformed to 100, and the least preferable value to 0. The intermediate values are transformed to numbers between from 100 to 0 according to the relative distances from the most and the least preferable values. For this transformation, a 'value function' which defines the relationship between original and transformed values is assumed. There are several methods which can be used to elicit a value function, but they are mostly based on the decision maker or expert's judgement. The transformed numbers represent the 'relative strength of preference' of the alternatives on a corresponding criterion.

In this study, considering that the lowest cost and environmental score best meet the two decision criteria, the most preferred option is assigned a preference score of 0, and the least preferred a score of 100. Scores are assigned to the remaining options so that differences in the numbers represent differences in strength of preference (Figure 2.4). In other words, a linear type form for the value function is assumed for cost and environmental score transformation.

In order to make a decision, the decision maker needs to combine the values for the different attributes to gain a view of the overall score. An intuitively appealing way of achieving this is to attach weights to each of the attributes that reflect their importance to the decision maker. The problem with importance weights is that they do not take into account the range between the least- and most-preferred options on each attribute. For example, if the options perform very similarly on a particular attribute, so that the range between worst and best is small, then this attribute is unlikely to be important in the decision, even though the decision maker may consider it to be an important attribute. This problem can be avoided by using the concept of 'swing weights'. These are derived by asking the decision maker to compare a change (or swing) from the least-preferred to the most-preferred value on one attribute to a similar change in another attribute [63]. In this study, weighting factors for cost and environmental score can be determined considering their relative importance and their range of distribution.



where, $s_C = \left(\dfrac{C - C_{min}}{C_{max} - C_{min}} \right) \times 100$, $s_E = \left(\dfrac{E - E_{min}}{E_{max} - E_{min}} \right) \times 100$

Figure 2.4 Relative strength of preference.

By adopting the above concepts related to relative strength of preference and weighting factors, the overall weighted score can be calculated using additive or linear modelling, i.e.

$$S_i = w_E s_{Ei} + w_C s_{Ci} \tag{2.3}$$

where, S_i : overall weighted score for i_{th} maintenance plan

w_E, w_C: weighting factors for environmental score and whole-life cost.

s_{Ei}, s_{Ci}: relative strength of preferences for environmental score and whole-life cost for i_{th} maintenance plan, respectively.

Thus, a maintenance plan with the smallest value of S_i becomes the best maintenance plan.

Figure 2.5 depicts schematically the tools and concepts used in this study and their flows. In short, several best maintenance plans on the non-inferior curve are determined by the 'outranking principle' or 'Pareto analysis', and then a single optimum plan which has the minimum S_i value can be calculated by introducing relative strength of preference, swing weighting and additive modelling.

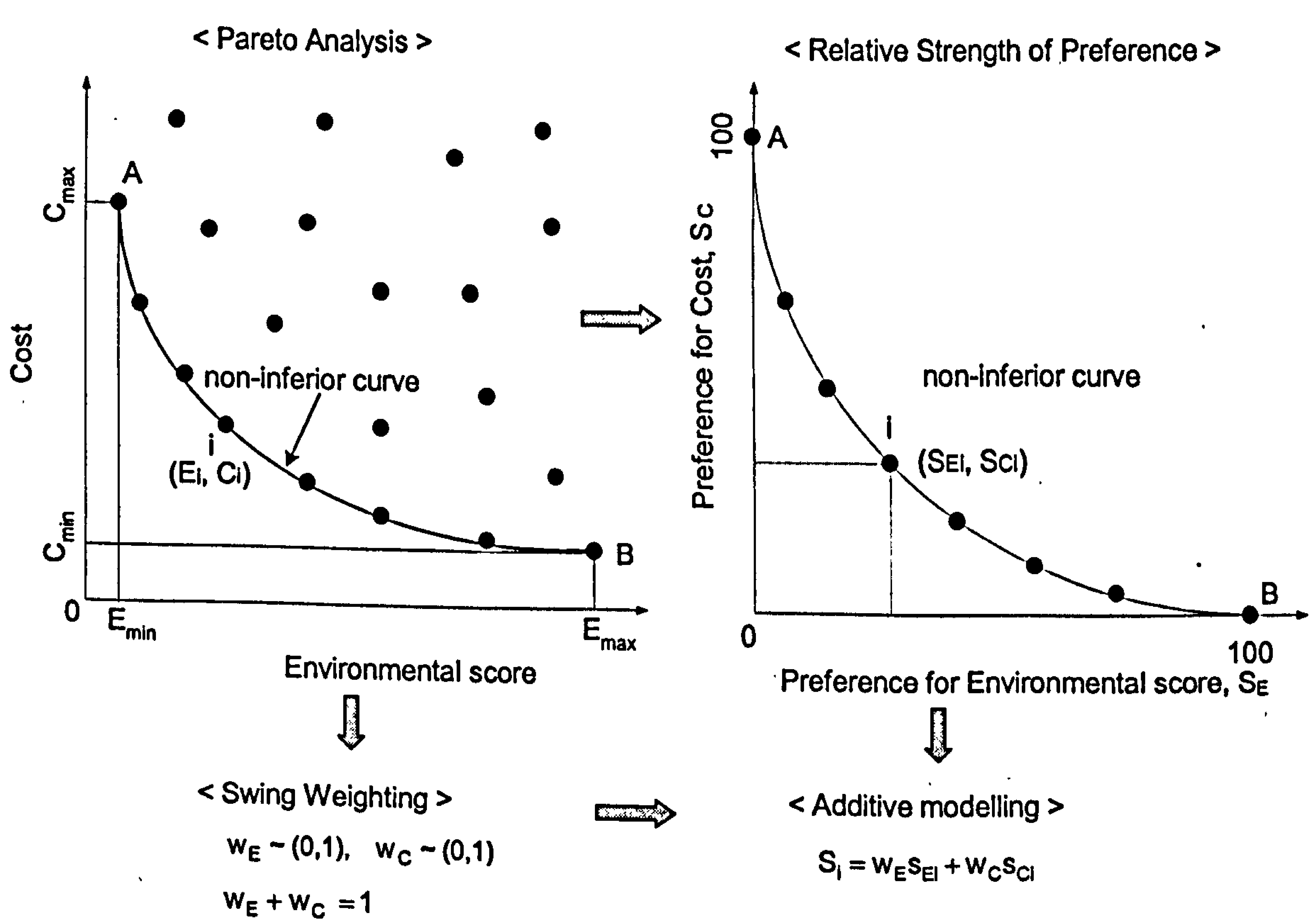


Figure 2.5 The framework of multi-criteria decision analysis in this study

2.3 Consideration of uncertainty in sustainable bridge maintenance

Figure 2.6 represents the selected methodologies in this study and their flow for sustainable bridge maintenance. The identification of the optimum maintenance plan depends on the outputs of each step, and in turn the outputs of each step rely on the input data and assumptions used. Therefore, the input data and assumptions have a great influence on the selection of best maintenance plans. For this reason, input data should be prepared to represent as much as possible the real situation. In reality, due to limited knowledge and incomplete modelling and idealisations, uncertainty is introduced into the input data. In this study, an attempt to deal with the uncertainty is made through the introduction of probabilistic modelling and analysis.

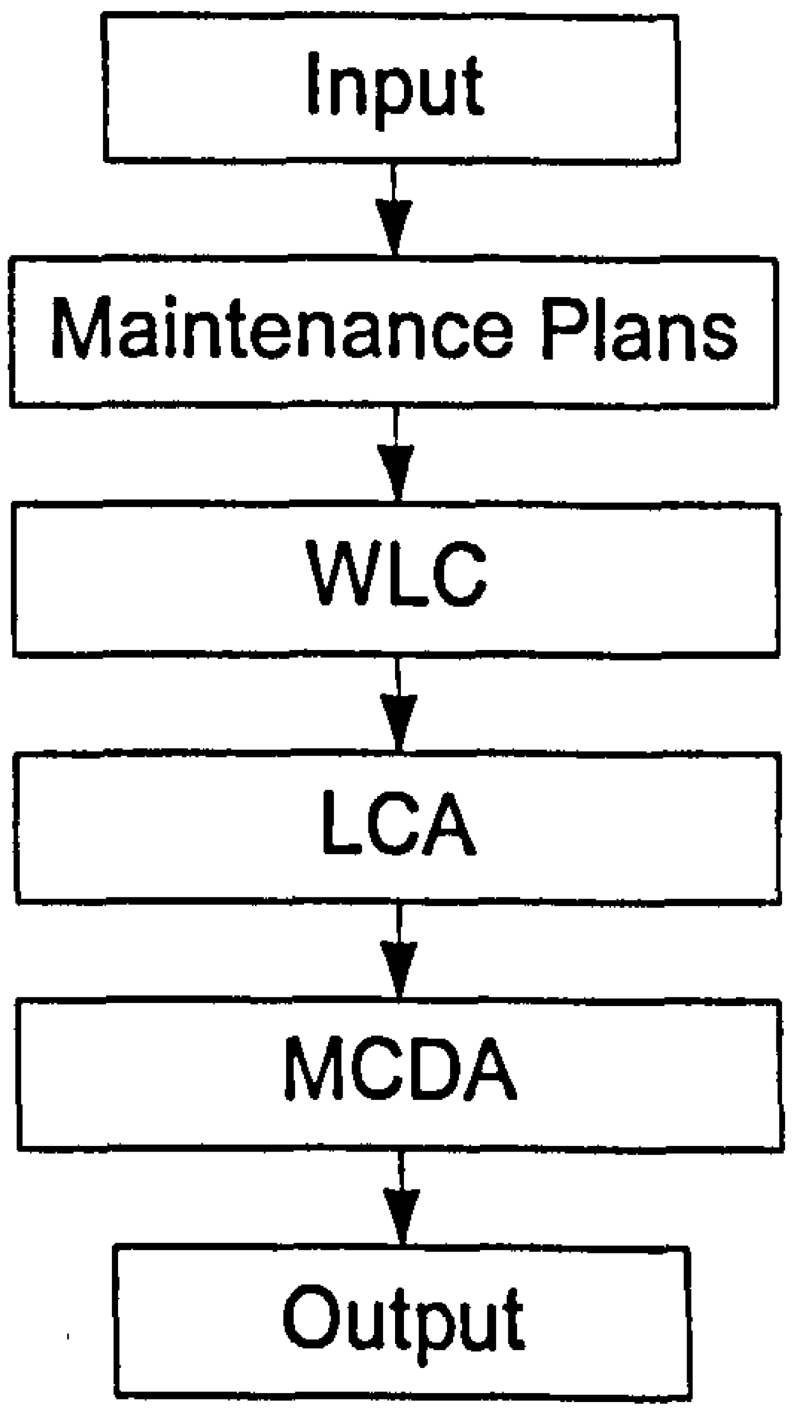


Figure 2.6 The approach for sustainable bridge maintenance

Normally, the analysis type can be categorised as deterministic or probabilistic depending on the nature of the input data. Deterministic analysis uses fixed data, and through the tools and processes fixed outputs are produced. If the data has no or little uncertainty, this approach can lead to a meaningful output. However, if the input data or modelling assumptions are uncertain, a probabilistic analysis can give more realistic outputs.

Bridge management is underpinned by the prediction of future performance of bridge structures, and so it inevitably contains uncertainty. Therefore, the treatment of uncertainty has been an important issue in the development of bridge management processes [64-66]. The scope of sustainable bridge maintenance is even broader than the traditional bridge maintenance, since additional tools and criteria such as LCA and MCDA have to be adopted. The inherent uncertainty in these tools is also a complex and important issue [67-70]. Therefore, it is imperative that the presence of uncertainty should be treated in any methodologies developed for sustainable bridge maintenance.

Treatment of uncertainty in sustainable bridge maintenance has to be integrated across all used methodologies. As a starting point, a review of the uncertainties in each methodology will be presented. Therefore, the uncertainties in the development of maintenance plans, WLC and LCA will be reviewed in the following Chapters, i.e. 3, 4 and 5, respectively, and a possible way to put these uncertainties together into an integrated framework will be suggested in Chapter 6.

Chapter 3

The generation of maintenance plans

3.1 The practice of bridge maintenance

Bridge maintenance activities can be considered as a group of actions against adverse user related or environmental influences on bridge structures. Therefore, in order to choose effective bridge maintenance options, it is necessary to understand the dominant deterioration mechanism and their causes.

The representative materials used for the construction of bridge structures are masonry, concrete and steel. Masonry structures have proved to be extremely durable and can last almost indefinitely with minimum maintenance [36]. Concrete on its own could creep, crack and suffer from erosion, even though its strength typically increases with time. However, in most cases steel will corrode unless protected, and this has a harmful effect on durability and, if left unchecked, even the safety of reinforced and pre-stressed concrete as well as steel bridge structures. It could be argued that most of the deterioration in bridge structures is related to the corrosion of steel, either exposed to the atmosphere or embedded in concrete. Therefore, understanding of the corrosion process is an essential starting point in order to reach good practice in bridge maintenance. The corrosion mechanisms are briefly summarised below mainly based on *Corrosion of Steel in Concrete* written by Broomfield [71].

3.1.1 Mechanism of corrosion

Firstly, corrosion of steel, i.e. the oxidation of steel, takes place by a series of electrochemical reactions. These are:

$Fe \rightarrow Fe^{2+} + 2e^-$	: The anodic reaction	(3.1)
$2e^- + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^-$	: The cathodic reaction	(3.2)
$Fe^{2+} 2OH^- \rightarrow Fe(OH)_2$	: Ferrous hydroxide	(3.3)
$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$	: Ferric hydroxide	(3.4)
$2Fe(OH)_3 \rightarrow Fe_2O_3.H_2O + 2H_2O$	: Hydrated ferric oxide (rust)	(3.5)

From the above reactions, it is evident that water and oxygen are two factors which activate the corrosion process in steel. Therefore, a number of maintenance options are related to preventing water and oxygen from contact with exposed or embedded steel.

In the case of steel in concrete, the steel is protected from corrosion by the formation of a passive layer due to the highly alkaline environment created by the pore water. The microscopic pores in concrete contain high concentrations of soluble calcium, sodium and potassium oxides. These oxides form hydroxides, which are very alkaline, when water is added. A passive layer is a thin, dense layer of iron oxides and hydroxides with some mineral content, which, when fully established, leads to a very slow rate of oxidation (corrosion). The corrosion of steel in concrete takes place when the high alkaline passive layer is broken down. The two main causes for breakdown of the passive layer are carbonation and chloride attack. Therefore, many maintenance options for reinforced concrete structures are associated with prevention of carbonation and chloride attack.

Carbonation is the result of the interaction of carbon dioxide gas in the atmosphere with the alkaline hydroxides in the concrete. Carbon dioxide dissolves in water to form an acid (Eq. 3.6), and this carbonic acid neutralizes the alkalis in the pore water, mainly forming calcium carbonate and water (Eq. 3.7). As a result of carbonation, the pH of concrete falls to a level where steel will start corroding. However, carbonation damage is rare on modern highway bridges in which water/cement ratios are low, and cement contents are high with good compaction and curing. Furthermore, there is usually enough cover to prevent the carbonation front from advancing into the concrete to the depth of the steel during the service life of the structure [71].

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (3.6)$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O \quad (3.7)$$

The chloride attack mechanism is different from carbonation. The chloride ion in solution reaches the steel either through cracks or by diffusion through the concrete's pore water. In either case, when the chloride ion reaches the threshold level, the steel spontaneously rusts. The natural rusting of steel in chloride-ion-contaminated concrete takes place as follows: Iron changes to a positively charged iron ion and releases two negatively charged electrons at the corroding site (Eq. 3.8). Iron ion complexes with the chloride ion at the corroding site (Eq. 3.9). Iron chloride complex reacts with water and the hydroxyl ion in the water at the corroding site and forms iron hydroxide, leaving one hydrogen and two chloride ions in the pore water at the corroding site (Eq. 3.10). The chloride ion in the pore water is now free to bond with more iron and continues the spontaneous corrosion process. The iron hydroxide reacts with oxygen and water to form rust plus water (Eq. 3.4 and Eq. 3.5). At the non-corroding site, the cathodic reaction (Eq. 3.2) takes place, and hence an electrical circuit is complete [72].

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (3.8)$$

$$Fe^{2+} + 2Cl^- \rightarrow Fe(Cl)_2 \quad (3.9)$$

$$Fe(Cl)_2 + H_2O + OH^- \rightarrow Fe(OH)_2 + H^+ + 2Cl^- \quad (3.10)$$

In summary, most of the maintenance options of bridge structures could be considered as a countermeasure against water, oxygen, carbonation, chloride attack, and/or their combinations. Keeping this in mind, the details of maintenance options and their categorisation shall be described in the next section.

3.1.2 Types of maintenance options

Effective bridge maintenance can be achieved by appropriate application of durability options for new structures and maintenance options for existing structures. The selection of durability options for new structures has an impact on the choice of subsequent maintenance options and their application timing. A range of durability options for new bridge structures can be found in BD 57/01 [73] and BA 57/01 [74]. They are shown below; some can be re-applied to existing structures.

- Continuous bridge decks
- Integral bridges (or integral abutments)
- Provision of suitable access facilities
- Good selection of deck expansion joints
- Waterproofing systems on the bridge deck
- Positive drainage system
- Concrete impregnation
- Enhanced concrete quality reinforcement cover
- Stainless steel reinforcement
- Non-ferrous reinforcement
- Plain concrete
- Protective coatings for steelwork
- Weathering steel
- Enclosure systems

On the other hand, maintenance options for existing structures can be categorised into routine, preventative and essential maintenance according to their purpose and their application timing.

Routine maintenance indicates minor activities which need to be carried out at regular intervals. Examples of routine maintenance include cleaning of drains and channels, removal of debris from bearing shelves and removal of graffiti/vegetation from an element [75]. Because routine maintenance is simple and executed at regular intervals, it is not taken into account when maintenance strategies are compared.

Preventative maintenance is maintenance work that is not essential now but may be justified on economic grounds. Preventative works are applied to slow down the rate of deterioration before structures are damaged or to repair the damage caused by deterioration and to slow down the rate of future deterioration. Vassie classified them further as preventative maintenance and remedial/repair work [76], but in this study they are grouped together as preventative maintenance. Examples of preventative maintenance are waterproofing, concrete impregnation, anti-carbonation coatings, concrete repair, cathodic protection, protective coatings of steelwork, and enclosure system, etc. Most of the options can be considered as preventative maintenance.

Table 3.1 Maintenance options, their categorisation and concerning factors

Maintenance options	Bridge type	Maintenance type	Acting against
Positive drainage	All	Routine	water, chloride
Waterproofing	All	Preventative	water, chloride
Protective coatings for steelwork	Steel	Preventative	water, chloride
Enclosure systems	Steel	Preventative	water, chloride
Concrete impregnation	Concrete	Preventative	chloride
Anti-carbonation coatings	Concrete	Preventative	carbonation
Corrosion inhibitors	Concrete	Preventative	chloride, carbonation
Cathodic protection	Concrete	Preventative (remedial)	chloride, carbonation
Desalination	Concrete	Preventative (remedial)	chloride
Realkalisation	Concrete	Preventative (remedial)	carbonation
Concrete repair	Concrete	Preventative (remedial) / Essential	chloride, carbonation
Replacement of element	All	Essential	chloride, carbonation

Essential maintenance is work required to maintain safety standards. If the essential maintenance cannot be carried out for some reason, other measures such as width or weight restriction have to be employed as an interim means [77]. In this study, essential maintenance is considered to be applied when the safety index reaches its target/permissible level, and a representative example of essential maintenance is replacement of element.

Table 3.1 summarises representative maintenance options, their nature and their intended effectiveness. The selection of maintenance options depends on material type, damage type and its severity/extent, and relevant environmental factors. Different maintenance options are described in detail below.

3.1.3 Maintenance options for water control

Positive drainage systems

The most serious source of bridge damage is 'salty water' leaking through badly maintained drainage systems or expansion joints in the deck. Therefore, the provision of a well designed and maintained drainage system and expansion joints is crucial in bridge management.

According to *Water management for durable bridges* published by Transport Research Laboratory [78], drainage system for bridges can be split into three elements. They are surface drainage, sub-surface drainage, and abutment drainage. Furthermore, in order to prevent leakage at expansion joints, it is recommended that drainage should be provided beneath joints in the form of a secondary seal. The details of drainage systems are not described here. *Water management for durable bridges* [78] and the Highways Agency's document, HD 33/96 *Surface and sub-surface drainage systems for highways* [79] are useful to understand the details of drainage systems and to find relevant references.

Even though the provision and maintenance of drainage systems is so important, it forms part of the durability options and routine maintenance. Therefore, it is not considered as a selective maintenance option in this study.

Waterproofing

Waterproofing on bridge decks creates an additional bridge element which prevents surface water from coming into contact with the structure. Normally, bituminous road surfacing materials are not sufficiently waterproof to protect bridge decks. Therefore, in the UK, it is recommended that bridge decks are waterproofed and surfaced in accordance with BD 47/99 [80] and BA 47/99 [81].

The waterproofing system comprises a concrete primer, a bonding agent, a ventilation layer, a waterproofing membrane, a protection board and a tack coat [71]. Depending on the selected waterproofing system, some of these layers can be omitted. Table 3.2 shows the categories of representative waterproofing systems. More details and specific site installation practice can be found in TRL reports [78, 82].

Table 3.2 Categories of waterproofing systems (Adapted from [78])

<table>
<tr><th colspan="2">Waterproofing system</th><th>Description</th></tr>
<tr><td rowspan="3">Sheet membrane system</td><td>Pour and Roll sheet system</td><td>Bituminous sheet bonded to the deck by molten binder</td></tr>
<tr><td>Torch-on sheet system</td><td>Bituminous sheet bonded to the deck by heating binder on underside of membrane</td></tr>
<tr><td>Self-adhesive sheet system</td><td>Bituminous sheet bonded to the deck by adhesive on underside of membrane</td></tr>
<tr><td colspan="2">Liquid applied system</td><td>Reactive resinous membrane applied by squeegee</td></tr>
<tr><td colspan="2">Mastic asphalt system</td><td>Rarely used nowadays and not recommended</td></tr>
</table>

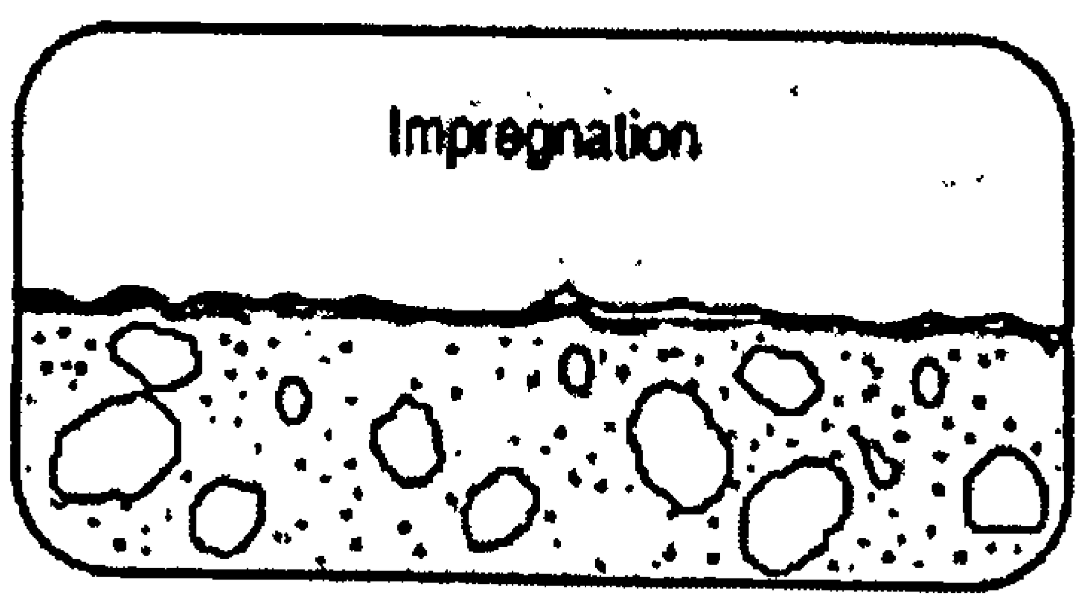
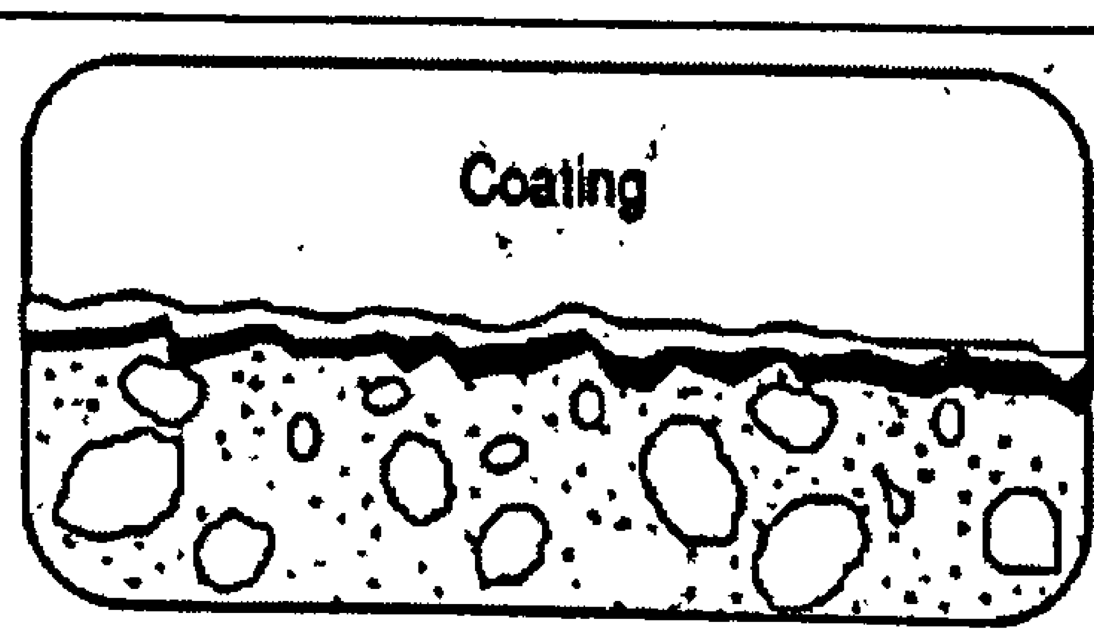
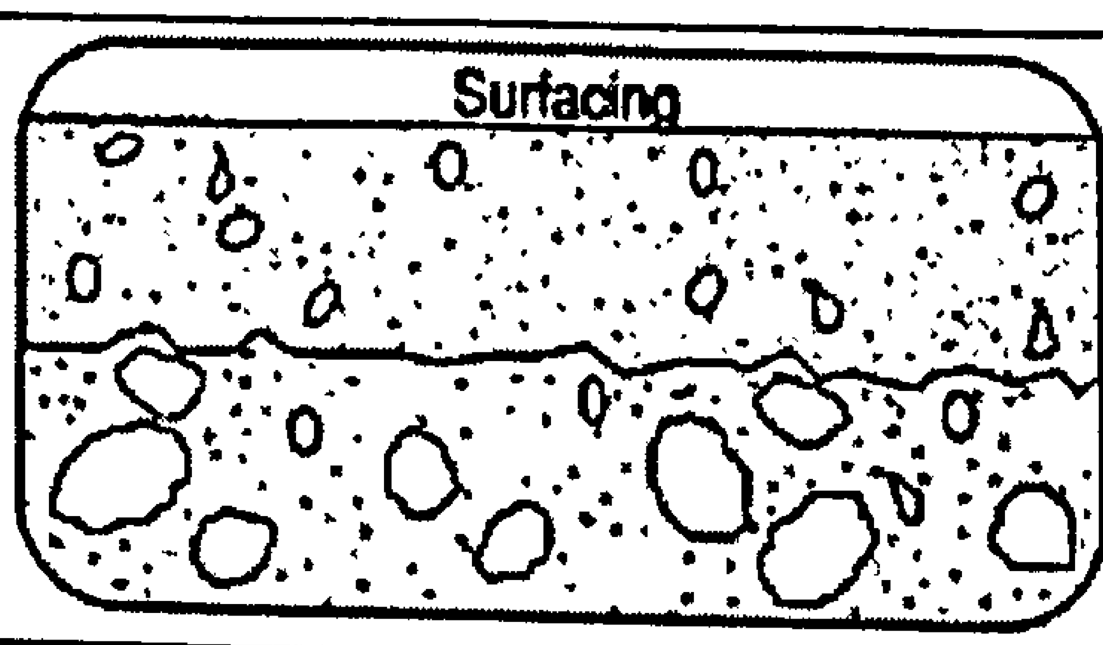
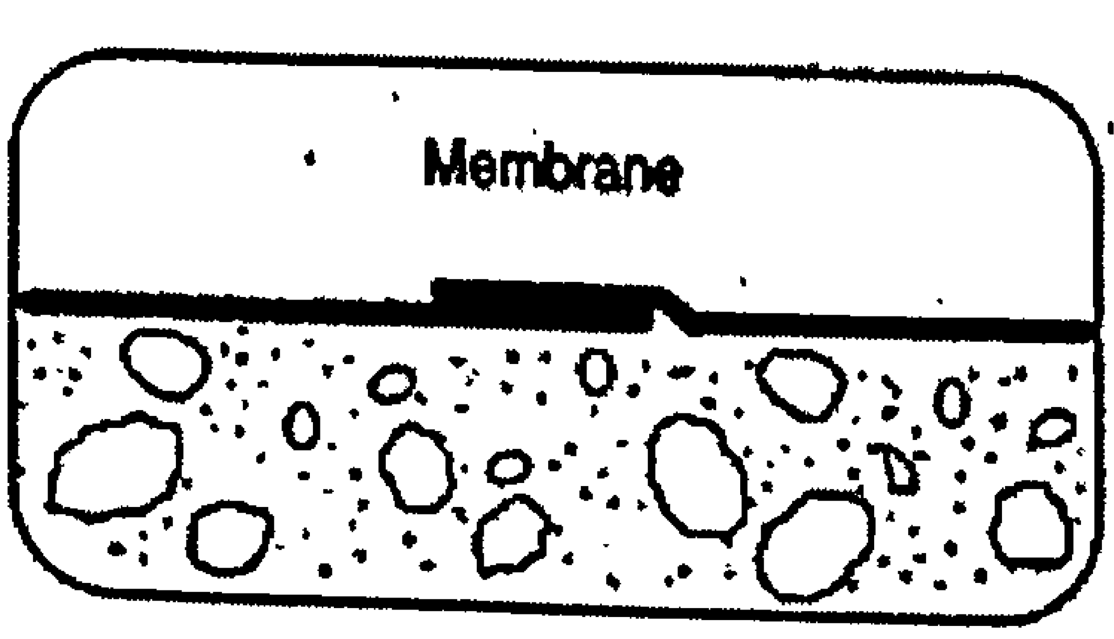
The majority of modern bridges have a waterproofing system applied at the time of construction, but this is not necessarily the case for older bridges [75]. Furthermore, the lifetime of the waterproofing membrane is 10-15 years [71]. This means that waterproofing systems in existing bridge structures need to be replaced or repaired. It is desirable that the replacement of deck waterproofing system is undertaken in conjunction with pavement reconstruction to minimise traffic disruption.

3.1.4 Maintenance options for concrete bridges

3.1.4.1 Protection of concrete surfaces

In order to isolate or modify the aggressive surrounding condition of concrete structures, many of the surface protection methods can be used. The range of barriers which can be applied onto concrete surface is huge, but they can be classified into four main groups: impregnation, coating, surfacing and application of elastomeric membranes [83]. Table 3.3 gives a brief description of each method.

Table 3.3 Surface protection methods of concrete structures (Adapted from [83])

Methods	Descriptions
	Treatment of a concrete surface with a material which subsequently penetrates into the pore structure. There are three basic types: (1) hydrophobic, (2) partial filling, and (3) filling. Typical uses of this method include chloride and carbon dioxide screens and protection against freeze-thaw damage
	The process of applying a film-producing material to a concrete surface. Many organic and inorganic coatings are available. Typical uses include chloride and carbon dioxide barriers, freeze-thaw protection, chemical-resistant barriers and aesthetics.
	The process of placing material on a concrete surface to form a uniform, thick layer on that surface. Surfacing is also known as: overlayment, rendering, plastering, or jacketing. Typical applications include: bridge deck overlays, chemical resistant floors, and carbonation barriers
	The process of placing material on a concrete surface to form an elastomeric film. The primary function of elastomeric membranes is to minimise liquid absorption by concrete. Elastromeric membranes differ from coatings because of the membrane's ability to move and flex without rupture. Typical applications include: traffic decks, plaza decks, and below grade waterproofing.

The practice of application of surface protection methods to bridge structures differs from country to country. In the USA, penetrating sealers such as silanes and siloxanes, or their combinations were used for the protection of bridge decks. The service lives of penetrating sealers (silanes and siloxanes) applied to decks range from 5 to 7 years, and hence should be reapplied every 6 years. On the other hand, for the protection of superstructures and substructures, both penetrating sealers and coatings are used [72].

In the UK, the application of silane impregnation is well established, and the use of coatings is recommended in limited situations. They are briefly described below.

Silane impregnation

BD 43/03 [84] recommends the use of impregnation for reinforced and prestressed concrete members immediately after construction as well as for structures in service, where corrosion is not yet occurring, in order to provide additional protection against chloride attack. Impregnation using hydrophobic pore-lining materials involves treating the concrete surface to form a water-repellent but vapour-permeable layer, which helps protect the concrete from the ingress of water and salt and provides added protection against reinforcement corrosion.

Generally, in the UK, silane has been used for impregnation of concrete. Silane is a generic descriptor, and the use of monomeric alkyl (isobutyl) – trialkoxy silane with a minimum active content of 92% is required by the current Specification for Highway Works and the Notes for Guidance [84].

Impregnation undertaken in the UK is known to be effective for at least 15 to 20 years, provided it is applied correctly, and may even last for much longer. However, concrete surfaces subject to physical abrasion and degradation mechanisms may be subject to shorter service lives, through loss of the impregnated surface. Furthermore, once sufficient chlorides are present at reinforcement depth then application will not stop corrosion but may reduce the corrosion rate.

Anti-carbonation coatings

BA 85/04 [85] suggests that concrete surfaces can be protected with anti-graffiti and anti-carbonation coatings. However, it is recommended that anti-graffiti coatings should be avoided wherever possible. Likewise, anti-carbonation coatings are usually only used in association with specialised remedial treatments such as electrochemical chloride removal, or if concrete deterioration by carbonation is likely or has occurred. The latter is a relatively rare occurrence on highway structures. The performance data for a number of coating products against carbonation are available in a BRE information paper [86].

Corrosion inhibitors

A corrosion inhibitor is a substance which when added to the corrosive environment reduces the rate of the metal dissolution. Corrosion inhibitors have been considered as a way to improve durability of new concrete structures [73], and also have drawn some attention as an option to stop corrosion in existing structures [71].

There is no general theory of corrosion inhibition in concrete because the mechanism is dependent to a large extent on the particular inhibitor [87]. However, the principle of most inhibitors is to develop a very thin chemical layer usually one or two molecules thick, on the steel surface, that inhibits the corrosion attack. Inhibitors can prevent the cathodic reaction, the anodic reaction or both. These inhibitors can be applied as coatings on the surface or on to the exposed steel at patch repairs, incorporated into the patch repairs, applied in grooves or drilled holes in the concrete cover or incorporated into concrete overlays [71].

The inhibitors are classified as surface applied migrating inhibitors and concrete admixture cast-in inhibitors. According to the draft BD 36 [75], surface applied migrating inhibitors may be only effective on poorer grades of concrete, and concrete admixture cast-in inhibitors are currently advocated only in new reinforced construction in particularly aggressive environments. Their costs are relatively low, but their effective life is not known [87]. Considering the ambiguity regarding their performance and effective life, corrosion inhibitors are not compared with other maintenance options in this study.

3.1.4.2 Concrete repair

When concrete structures crack, spall, delaminate or crumble, concrete repairs are executed. According to Ryall [88], general steps of concrete repairs are as follows.

(1) To clean the concrete surface by removing dirt, debris and other deleterious materials.
(2) The area is marked out and the decayed concrete broken out using one (or a combination) of three methods: Hand held hammer and chisel; Pneumatic hammers; Hydrodemolition.
(3) The reinforcement is cleaned of corrosion products by grit blasting and primed with a zinc rich primer or a wet cementitious powder mix.
(4) The repair is carried out by hand/trowel, fluid or spray application.

Table 3.4 extracted from the draft BD36 [75] provides statistical data of possible concrete repair methods and their unit cost. This table shows that the employed concrete repair methods may change depending upon exposure conditions, maintenance intervals, and the resulting size of defect area. It implies that a variety of concrete repair scenarios can be made and it makes the decision making process more complex.

Another confusing factor in concrete repairs is the wide spectrum of materials available. Earlier concrete repair was carried out using standard Portland cement based mortar, but now materials range from pure polymers to polymer modified Portland cement based products. According to a TRL report [87], representative repair materials are:

Table 3.4 Data for concrete repairs (Extracted from [75])

Structures	Exposure class *	Maintenance intervals (years)	Defect area	Concrete repair class **	Unit cost (£/m²)	Works duration rate (m²/week)
Reinforced concrete decks and main members, including substructures	[E1]	0-30	No defects			
		40	2%	[C1]	300	8
		50	5%	[C2]	600	4
		60	10%	[C3]	1200	2
	[E2]	10	2%	[C1]	300	8
		20	5%	[C2]	600	4
		30	10%	[C3]	1200	2
		40	20%	[C3]	1200	2
		50	30%	[C3]	1200	2
		60	40%	[C3]	1200	2
	[E3]	10	10%	[C3]	1200	2
		20	20%	[C3]	1200	2
		30	50%	[C3]	1200	2
		40	80%	[C3]	1200	2
		50	100%	[C3]	1200	2
		60	100%	[C3]	1200	2
Pre-stressed decks and main members	[E1]	0-30	No defects			
		40	2%	[C2]	600	4
		50	5%	[C3]	1200	2
		60	10%	[C3]	1200	2
	[E2]	10	-	-	-	-
		20	5%	[C3]	1200	2
		30	5%	[C3]	1200	2
		40	10%	[C3]	1200	2
		50	15%	[C3]	1200	2
		60	20%	[C3]	1200	2
	[E3]	10	5%	[C3]	1200	2
		20	10%	[C3]	1200	2
		30	20%	[C3]	1200	2
		40	30%	[C3]	1200	2
		50	40%	[C3]	1200	2
		60	50%	[C3]	1200	2

* Exposure class

[E1]: Protected, [E2]: Sheltered, [E3]: Severe

** Concrete repair class

[C1] General Patch Repairs: Typically small areas of repair<0.05m². Breakout with hand tools or mechanical breaker. Hand placed concrete.

[C2] Moderate Repairs: Typically areas > 0.05m², depth up to 100 mm. Breakout with mechanical breaker or waterjetting. Flowable or sprayed concrete.

[C3] Major repairs: Typically areas> 0.05m² and depth>100mm. Breakout with mechanical breaker or waterjetting. Flowable or sprayed concrete.

(1) Resinous materials: Epoxy mortar, Polyester mortar, Acrylic mortar.

(2) Polymer modified cementitious materials: Styrene butadiene modified, Vinyl acetate modified, Magnesium phosphate modified.

(3) Cementitious materials: Ordinary Portland cement/mortar, High alumina cement mortar, Flowing concrete.

In conclusion, various concrete repair methods exist, so suitable repair processes and materials should be selected for any given situation. For more information on concrete repairs, reference [89] published by Concrete Society and BD 27/86 [90] are also useful.

3.1.4.3 Electrochemical techniques

<u>Cathodic Protection</u>

Cathodic Protection (CP) is an electrochemical method for stopping corrosion caused by chloride attack or carbonation. Information on cathodic protection is provided in BA 83/02 [91], European standard BS EN 12696:2000[92], and other references [71, 93-98].

The principles of cathodic protection are straightforward. Corrosion occurs by the formation of anodes and cathodes on the reinforcement surface. Corrosion occurs at the anode; a generally harmless reduction reaction occurs at the cathode. By introducing an external anode and an electric current, the reinforcement is forced to become cathodic and reduces corrosion to insignificant levels. The cathodic protection anode is typically a material that is consumed at a negligible or controlled rate by the anodic oxidation reaction.

There are two types of cathodic protection systems, impressed current and galvanic (also known as sacrificial). However, galvanic anode systems have had limited use and are still considered experimental in the UK with applications to atmospherically exposed reinforced concrete structures.

A schematic of an impressed current system is shown in Figure 3.1. Impressed current cathodic protection consists of an anode system, a DC power supply and monitoring probes, with associated wiring and control circuitry. One of the key decisions is the choice of anode. The alternatives are conductive coatings applied to the concrete surface, mixed metal oxide coated titanium mesh or grid in a concrete overlay, conductive mortar and overlays, coated titanium ribbon in slots, or various discrete anode materials in holes in the concrete. Table 3.5 summarises the anode types and their relative performance. This information is indicative only and based on the experience in the UK to year 2000 [91].

Cathodic protection can be used as a preventative measure as well as remedial maintenance option. For new structures or structures in service when the chloride ions have not reached the steel and depassivation has not yet occurred, cathodic protection can be used to improve the corrosion resistance of steel by providing a small cathodic polarization of the steel/concrete interface. In older structures with corroding steel reinforcement, cathodic protection can decrease the corrosion rate of the reinforcement from significant to negligible values [92].

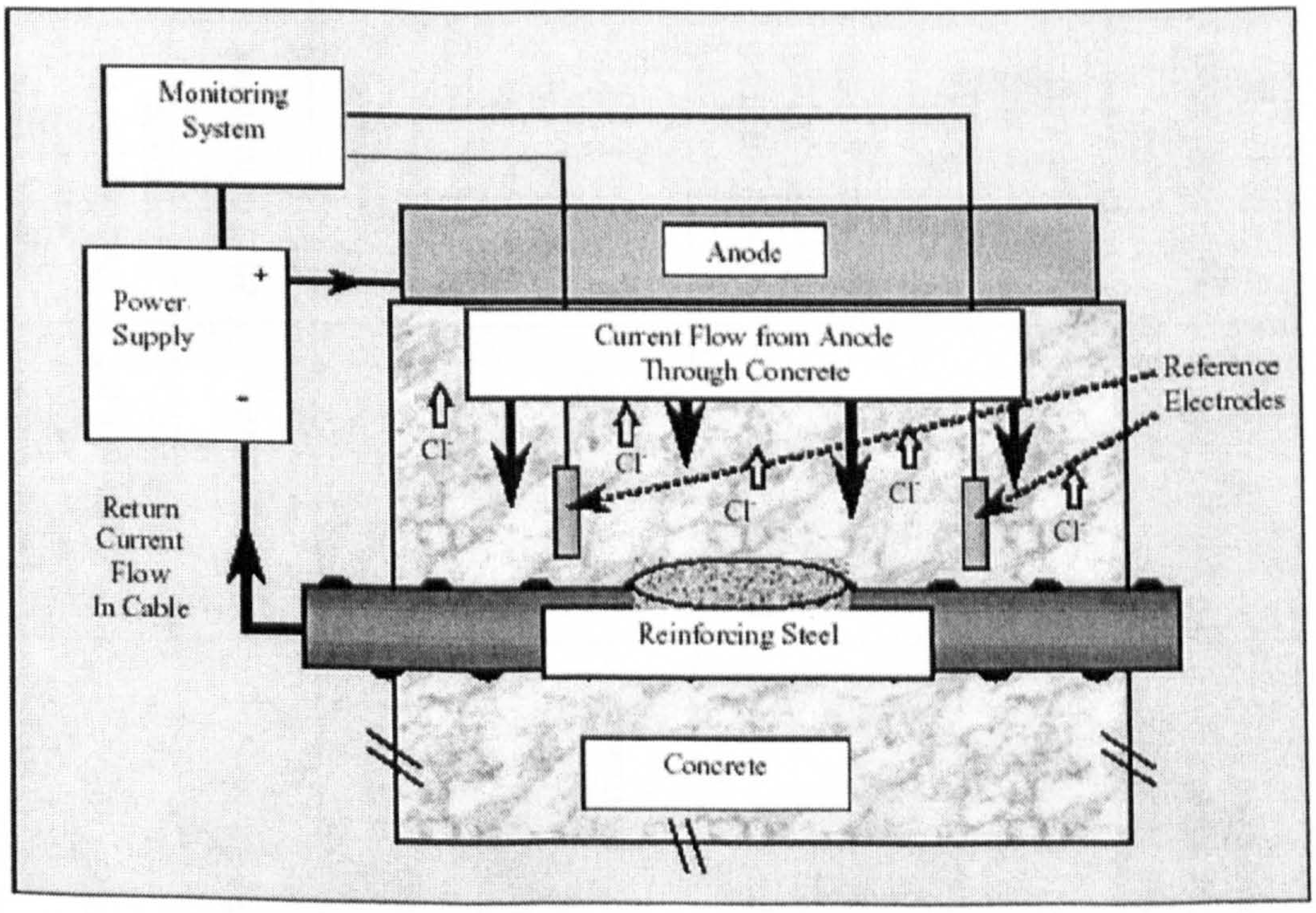


Figure 3.1 Schematic diagram of impressed current cathodic protection (from [91])

Table 3.5 Anode types and characteristics ([91])

Anode Type	Long Term Anode Current Density per m^2 of anode	Long Term Current Density per m^2 concrete	Supplier's Typical Anode Life Estimate	Suitable for Wet Structures	Suitable for Running Surfaces	Dimensional & Weight Impact/ Installation	Other Performance Queries	Typical Installed Cost (2000 costs)
Conductive Organic Coatings	20mA/m^2	20 mA/m^2 Max	Up to 15 years	No	No	No Painted	Some unproven products	£20-£40/m^2
Sprayed zinc	20mA/m^2	20mA/m^2 max	Up to 25 years	Possibly	No	No Thermal Spray	Limited UK experience	£60-£100/m^2
Mixed metal oxide coated titanium(MMO Ti) mesh and grid in cementitious overlay	110-220mA/m^2	15-110 mA/m^2 varying grades	Up to 120 years	Yes	Yes	Yes In circa 25mm overlay	Overlay Quality Control	£60-£100/m^2 including overlay
Discrete MMO Ti anodes, with carbonaceous surround	800mA/m^2 from carbonaceous surround	Circa 10-110 mA/m^2 subject to Distribution	Up to 50 years	Yes, not tidal	Yes	No Placed in predrilled holes		£40-£100/m^2
Discrete anodes in cementitious surround. MMO Ti or conductive ceramic	800mA/m^2	Circa 10-110 mA/m^2 subject to Distribution	Up to 50 years	Yes	Yes	No Placed into holes or slots		£40-£100/m^2
Cementitious overlay incorporating nickel plated carbon fibre strands	20mA/m^2	20mA/m^2 Max	Up to 25 years	Yes, not tidal	Yes, under wearing course	Yes Sprayed, circa 8mm thick	Limited	£30-£60/m^2

Chloride extraction

Chloride extraction (also known as desalination or chloride removal) is an electrochemical method intended for use on chloride contaminated concrete. For this, temporary power supplies, anodes and typically liquid in temporary shutters are arranged as shown in Figure 3.2. As an electrolyte, potable water and sometimes calcium hydroxide added water is used. The system operates on the same principle as cathodic protection but the current density is 1000 – 2000mA/m^2 (c.f. 10-20mA/m^2 for cathodic protection) and the treatment takes 3 to 15 weeks [91, 99].

Chloride extraction is achieved by applying a potential across a temporary anode, external to the concrete, and an internal cathode – the reinforcing bar. The positive anode attracts negatively charged chloride ions and the cathode repels the chloride ions. Chlorides are extracted into the liquid electrolyte for eventual disposal and very high levels of hydroxyl ions are generated at the steel.

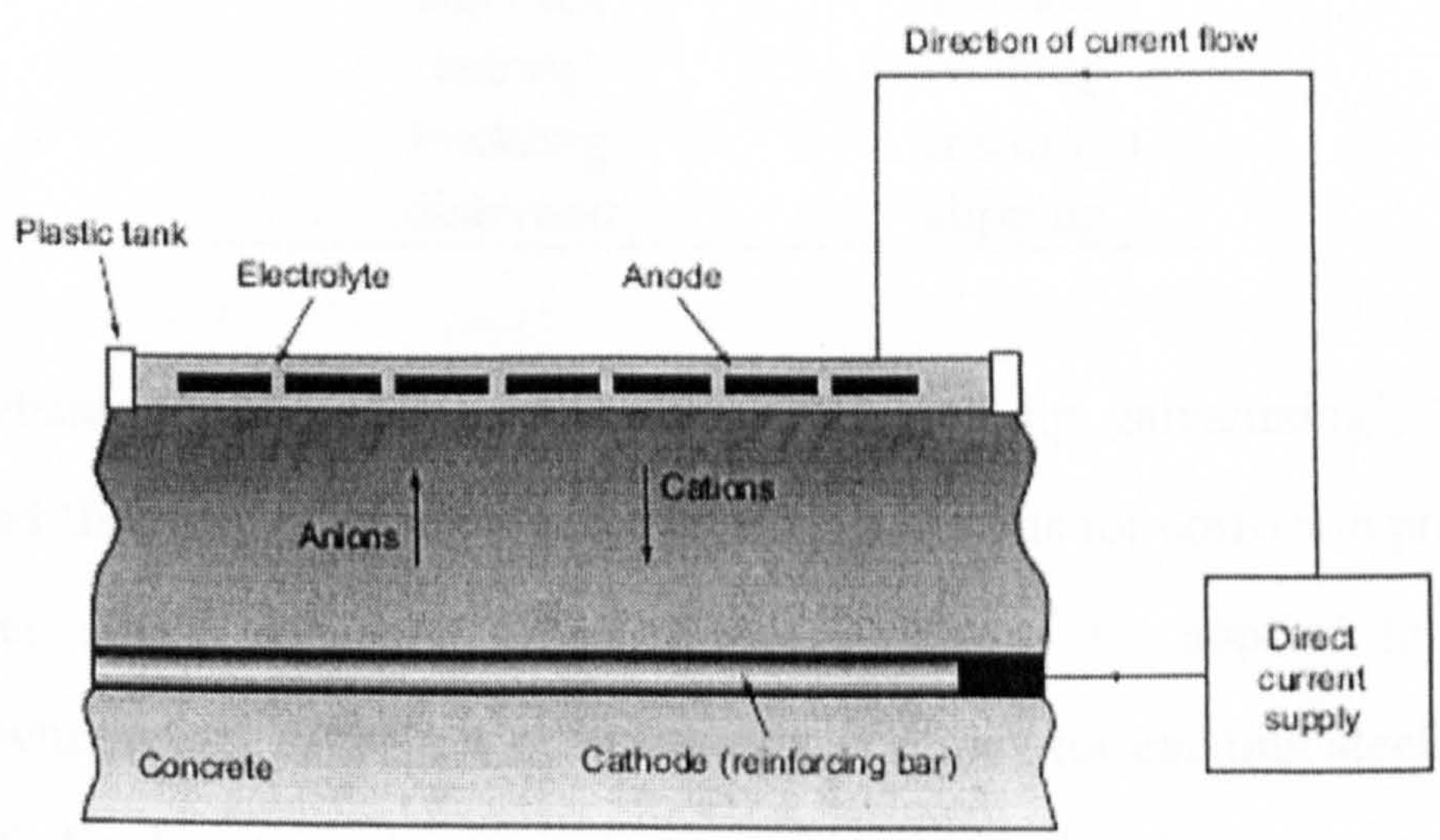


Figure 3.2 Schematic diagram of chloride extraction (from [87])

Realkalisation

Realkalisation is equivalent to chloride extraction but used where the structural concrete is carbonated. The process is similar to that of chloride extraction but the treatment time is typically 5-15 days. The electrolyte, which is an alkaline solution of sodium or potassium carbonate, diffuses into the concrete towards the reinforcement. The electrochemical production of hydroxyl ions caused by the electric current creates more alkalinity at the surface of the reinforcement and repassivates the steel. After the treatment, the alkalinity of concrete restores to a level greater than pH 10.5 [99].

3.1.5 Maintenance options for steel bridge

According to Ryall [88], damage to steel elements can be broadly classified as shown in Table 3.6. The most common damage type for steel bridges is corrosion, and normal maintenance activities of steel bridges are mainly related to prevention of corrosion of steelwork. Other damage comes from collision, fatigue and natural disasters (earthquakes and floods) and they can be repaired by many ways such as welding, cold stitching, and substitution of local elements or bolt, etc.

Table 3.6 Classification of damage to steel elements

Parent material	Fastenings
corrosion	corrosion
cracking	fracture
tearing	bending
buckling	cracking
distortion	slipping

Here, the characteristics of 'Weathering steel', 'Hot dip galvanizing', 'Protective coatings' and 'Enclosure Systems' are reviewed as options for corrosion protection of steel bridges. More precisely, the former two options are applied to new steel structures, whereas the latter two can be used as options for existing steel structures. The use of 'Enclosure systems' is limited to concrete/steel composite structures whose headroom within the enclosure is at least 1 m deep.

3.1.5.1 Weathering steel

Weathering steel is similar to mild steel except that it has additional alloying elements of copper, chromium and phosphorus [88]. When the weathering steel is exposed to atmosphere, the rusting process is initiated on the surface, similar to mild steel. However, the specific alloying elements in the steel produce a stable rust layer that adheres to the base metal and is much less porous. This rust 'patina' develops under conditions of alternate wetting and drying to produce a protective barrier, which impedes further access of oxygen and moisture [100]. Figure 3.3 illustrates the reduction of corrosion rate of weathering steel.

Weathering steels are generally specified to BS EN 10025-5:2004 [101] and guidance on its use in the UK is found in BD 7/01 [102]. Additional specific properties of weathering steel can be found in TRL report [103] and ECCS report [104].

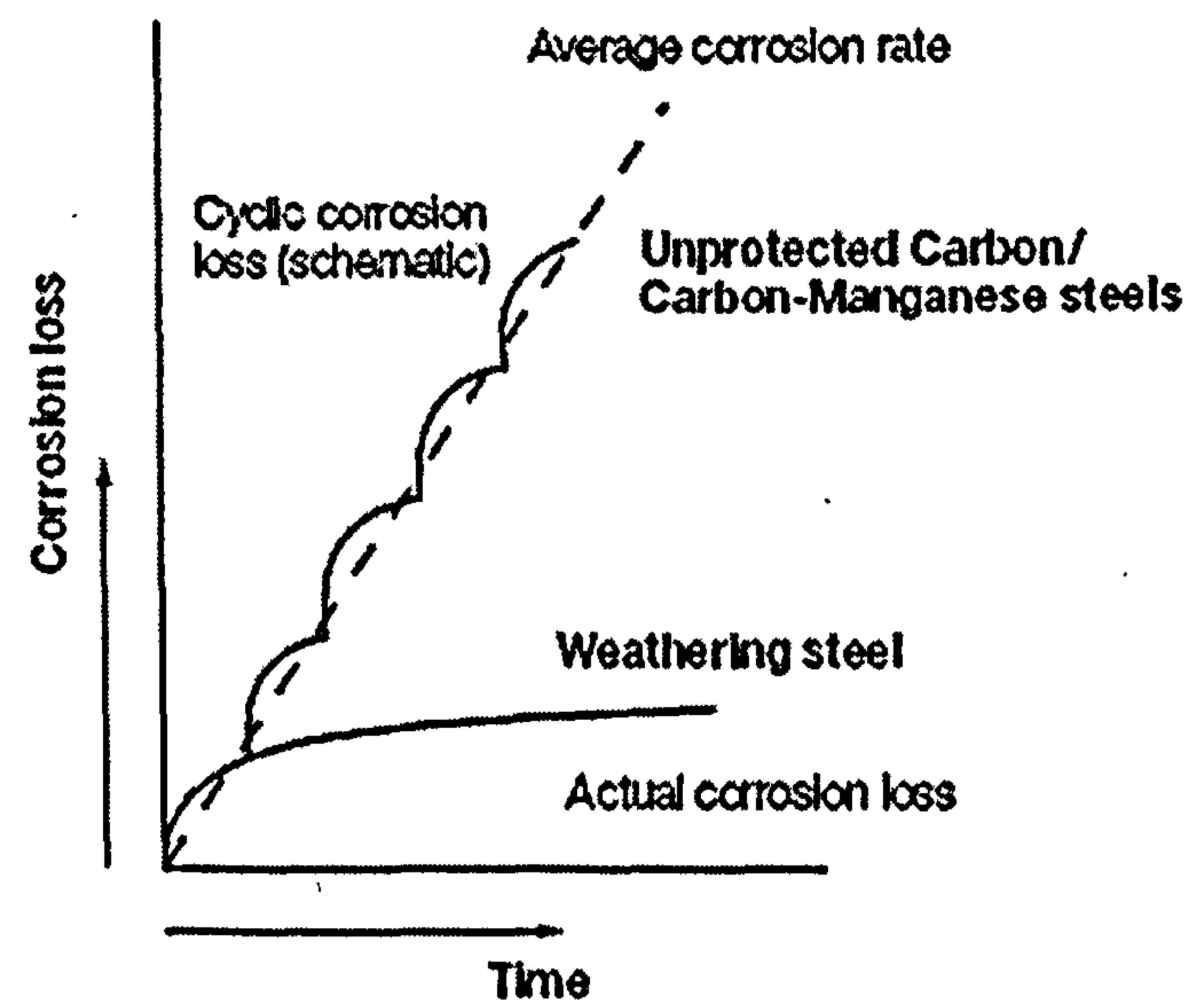


Figure 3.3 Schematic comparison between the corrosion loss of weathering and carbon steels ([100])

3.1.5.2 Hot dip galvanizing

The galvanizing of steel is a process whereby a layer of zinc is alloyed to its surface by dipping it into a hot bath (around 450℃) of molten zinc thus forming a 'tough, hard wearing' layer [88]. The galvanized coating provides cathodic corrosion protection as well as barrier protection. In other words, hot dip galvanizing protects steel because zinc weathers at a slow, predictable rate giving a long life (barrier protection) and zinc acts as a sacrificial anode to iron and steel and corrodes instead of steel (cathodic protection). The specification of hot dip galvanizing is found in BS 7371-6:1998 [105] and more details can be found in GA report [106] and AGA report [107].

3.1.5.3 Paints

The traditional way to protect steel is the use of a paint system. Paints are made by mixing and blending three main components of pigment, binder and solvent. The pigments are finely ground powders which provide colour, opacity, film-cohesion, and sometimes corrosion-inhibition. The binders are resins or oils. These are the film-forming components in the paint. The solvents are used to dissolve the binder and to facilitate application of the paint. After the paint has been applied as a 'wet film', the solvent evaporates leaving the binder and pigments on the surface as a 'dry-film'.

A painting system is made up of several layers of paints called primer, undercoats and finishing coats. The priming coat (primer) is applied directly onto the cleaned steel surface. Its purpose is to wet that surface and to provide adhesion for subsequently applied coats. In the case of primers on steel surfaces, these are usually also required to provide corrosion inhibition. The intermediate coats (or undercoats) are applied to 'build' the total coating thickness as required. The finishing coats provide the first-line defence against the environment and also determine final appearance in terms of gloss, colour, etc. Paints are classified by their pigmentation and/or binder types [108].

Annex A of BD 35/99 [109], *Manual of Paints for Structural Steelwork*, gives details for nine representative painting systems. They are

(1) Paints for oleo-resinous systems
(2) Paints for chlorinated rubber systems
(3) Paints for epoxy or epoxy based systems
(4) Vinyl/vinyl copolymer paints
(5) Bituminous coatings
(6) Special category coatings
(7) Polyurethane coatings
(8) Acrylated rubber coatings

(9) Grease paint coatings.

Selection of a suitable paint system is determined by the environment and accessibility. Reports published by SCI [110, 111], BS [108] and TRL [112] provide good guidance towards understanding and selecting of appropriate painting systems.

3.1.5.4 Enclosure systems

Enclosure systems were developed by TRL as an alternative method for the protection of bridge superstructure against corrosion in 1980s. This was based on the idea that if steel structures were enclosed against contaminants in the environment they could be rendered maintenance free for periods of at least thirty years. In a polluted environment, the levels of airborne particulate contaminants within an enclosure with controlled ventilation are much lower than the levels outside. Thus the enclosure results in a reduction of the rate of breakdown of the protective coatings and subsequent corrosion of the steelworks. The advantages of enclosure systems include:

- Cost savings in corrosion protection.
- The provision of permanent access for future inspection and maintenance.
- The reduction or elimination of traffic delay costs during construction, inspection and maintenance.
- Protection of concrete soffits eliminating the need for protecting coating.

The enclosure system comprises a protective shell of a durable material (glass-reinforced polymer, stainless steel, aluminium, etc). Information on the design of enclosure system is provided in BD67/96 [113] and BA67/96 [114].

3.2 The development of maintenance plans

3.2.1 Introduction

In section 3.1, various maintenance options for concrete and steel bridges are reviewed. Good practice in bridge management can be accomplished by applying a series of maintenance options to bridge structures. Different combinations of maintenance options produce different deterioration rates of bridge structures, and different economic and environmental impacts. Therefore, it is necessary to develop a number of feasible maintenance plans which comprise a series of maintenance options undertaken at different times. The target of sustainable bridge maintenance can be achieved by comparing the economic and environmental performances of different maintenance plans and choosing the optimised one. Keeping this in mind, this section explains how to develop or generate maintenance plans.

Bridge maintenance plans can be developed by considering different maintenance options and their combination. As already mentioned in 2.2.3, three approaches can be used to determine the time of application of maintenance options. They are

(a) time-based approach: applicable primarily to preventative maintenance actions;
(b) performance-based approach: applicable primarily to essential maintenance actions;
(c) time- and performance-based approach: applicable to both preventative & essential maintenance actions.

Previous research which developed maintenance plans was based on one of above three approaches. In turn, this leads to two methods, namely the effective life concept and the reliability-based approach. These two methods are described below.

3.2.2 Development of maintenance plans based on effective life concept

Rubakantha [64] and Vassie [76] introduced the effective life concept in the development of maintenance plans. According to this method, a maintenance option is chosen and at the end of its effective life a new option is chosen until the cumulative life of the maintenance options exceeds the remaining service life of the bridge or the time horizon used in decision making (Figure 3.4). The application time of the first maintenance option, i.e. maintenance free life, is determined by the types of durability options applied when a new structure is constructed or when the rehabilitation is executed.

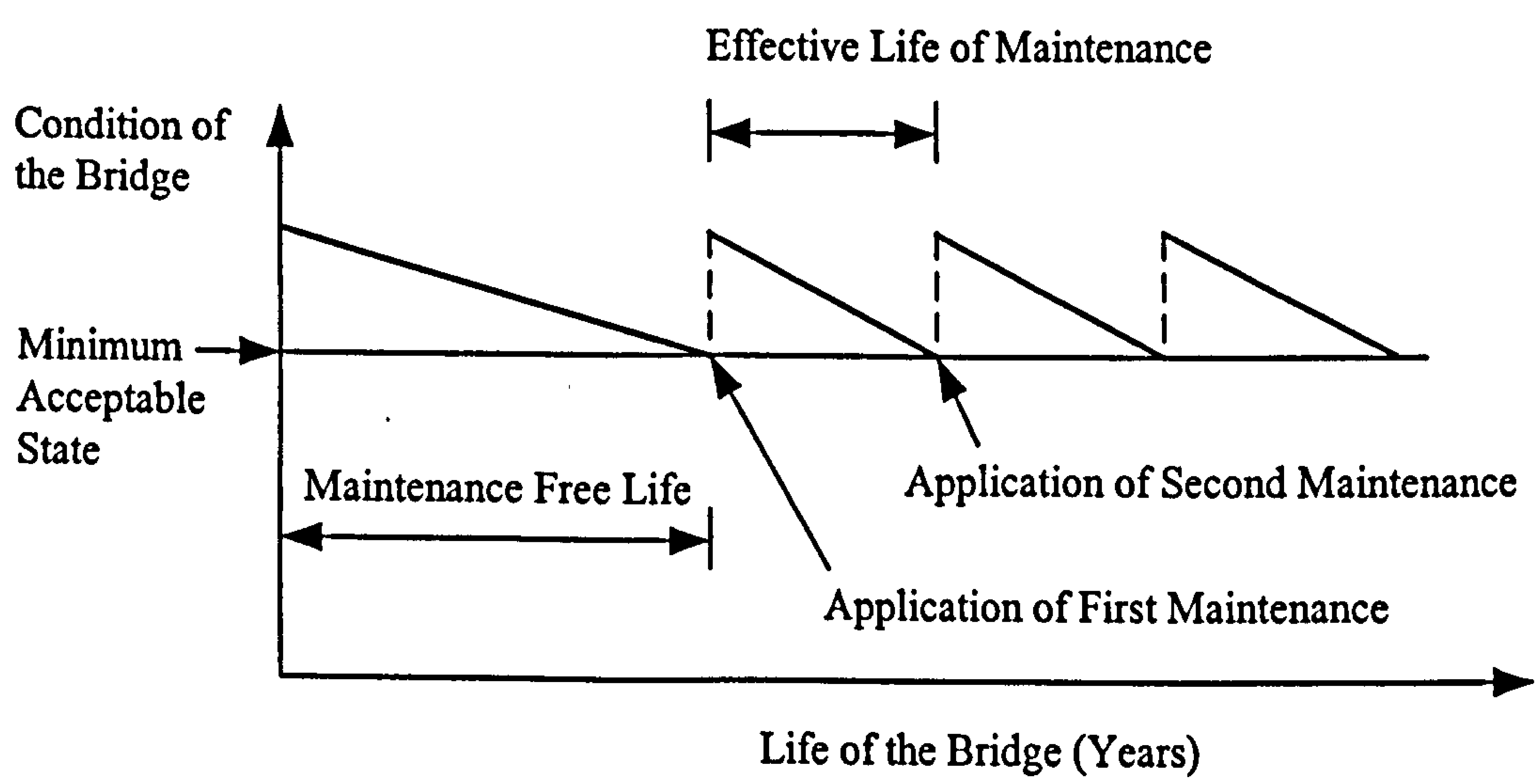


Figure 3.4 Determination of maintenance frequency by effective life concept

Rubakantha [64] considered 15 durability options and 5 maintenance options. He calculated the whole life costs of maintenance plans when different durability options are combined with different maintenance options. He showed that preventative maintenance options reduced the whole life cost significantly, and when combining the preventative maintenance regime with appropriate durability provisions at the design stage, a saving of up to 10% can be achieved over the whole life cost of a conventional design.

Similarly, Vassie [76] appraised the whole life costs of five different maintenance strategies for concrete bridges. These strategies were made by applying five different maintenance options separately. The maintenance options used were waterproofing, surface treatment, cathodic protection (minimum), cathodic protection (all), and cut out and repair (COR). He also concluded that the preventative maintenance options provide the best value for money.

In summary, the effective life concept was used as a traditional tool to develop bridge maintenance plans in the UK. This approach is relatively straightforward, but can not readily be coupled with bridge deterioration profiles and the need of rehabilitation in relation to key performance indicators.

3.2.3 Development of maintenance plans based on reliability index approach

In the above section, it was shown that the effective life concept was typically used to develop the future maintenance plans of bridge structures in the UK. However, from the late 1990s, the Highways Agency recognized the need for a new approach in which future maintenance activities of bridge structures are determined based on the changes of performance indicators such as the live load carrying capacity factor or the reliability index of bridge structures [115-117]. The research for a theoretical background to this approach was started mainly by Frangopol [118] and Thoft-Christensen [119, 120]. Subsequently, Frangopol and his fellow researchers [121-128] developed methodologies in order to predict future maintenance activities of bridge structures based on reliability index changes.

Briefly, this approach uses a bilinear relationship to model the safety or reliability index profile of bridge structures and takes account of the effects of preventative maintenance activities on the profile, finally calculating the application time of rehabilitation (or essential maintenance). With reference to section 3.2.1, this approach is a time- and performance-based approach.

Figure 3.5 shows schematically how to calculate the rehabilitation time with/without preventative maintenances based on this approach [121]. The variables used in this model in order to define the changes of profile are as follows. Without preventative maintenance, the variables are: initial or maximum reliability index β_0, time of damage initiation t_i, and reliability index deterioration rate α. Five additional variables which characterise the preventative maintenance plan are: time of first application of preventative maintenance t_{pi}, time interval of reapplication of preventative maintenance t_p, duration of preventative maintenance action on reliability t_{pd}, reduced deterioration rate of reliability index during preventative maintenance action θ, increase in reliability index (if any) immediately after the application of preventative maintenance action γ. The rehabilitation time is determined as the time needed for the profile to reach the target reliability index β_{target}.

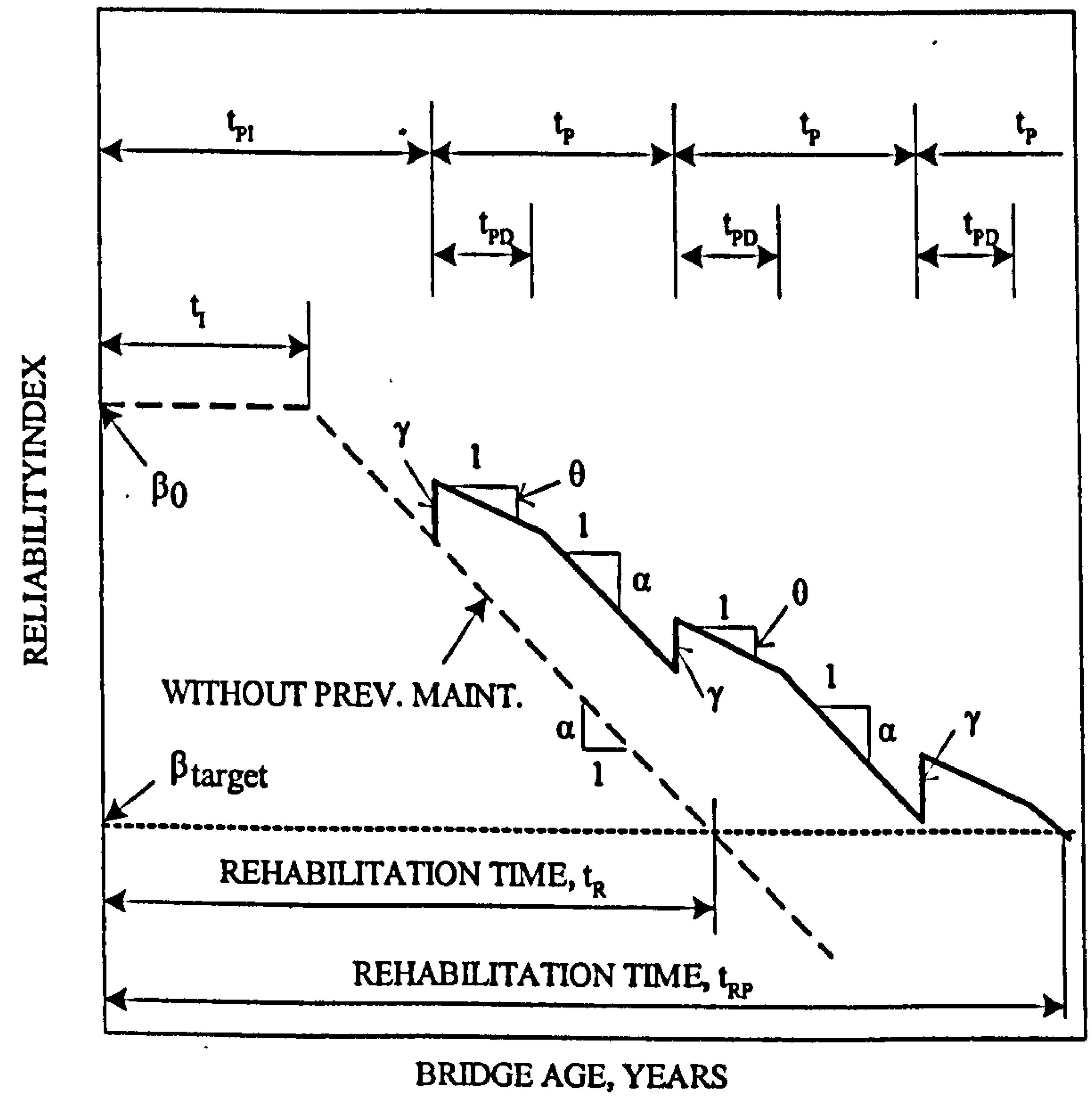


Figure 3.5 Time variation of reliability index with and without preventative maintenance ([121])

When more than one preventative maintenance options are used, an additional 5 variables per option should be determined to define the change of reliability index profile. However, the changes in reliability index as a result of applying different maintenance options are not well known.

Nevertheless, if the necessary variables are collected, this approach can model diverse maintenance strategies such as:

- do nothing
- do nothing + rehabilitation
- preventative maintenance only
- preventative maintenance + rehabilitation
- do nothing (partly) + preventative maintenance (partly) + rehabilitation

Figure 3.6 shows some examples of reliability index profiles associated with different maintenance strategies.

Furthermore, if there are several preventative maintenance options to be applied and if they are mixed with each other or with do nothing and rehabilitation actions, the number of generated maintenance plans becomes large. If it is assumed that more than one maintenance options may be applied at the same time, the number of feasible maintenance plans becomes enormous.

Hence, case studies presented in previous investigations introduce some limitations in generating maintenance plans. For example, only one preventative maintenance option was combined with rehabilitation, whereas a mix of preventative maintenance options or the inclusion of a do nothing strategy was not considered. In this respect, improvements in the available methodologies for generating maintenance plans are required.

In summary, the generation of maintenance plans based on effective life concept and reliability index approach has advantages as well as limitations. Two approaches are being developed in the UK and internationally. Therefore, this study will adopt these two approaches together in generating maintenance plans. However, some efforts will be given in order to automate the generation process and generate all feasible maintenance plans. More details will be given in Chapter 6.

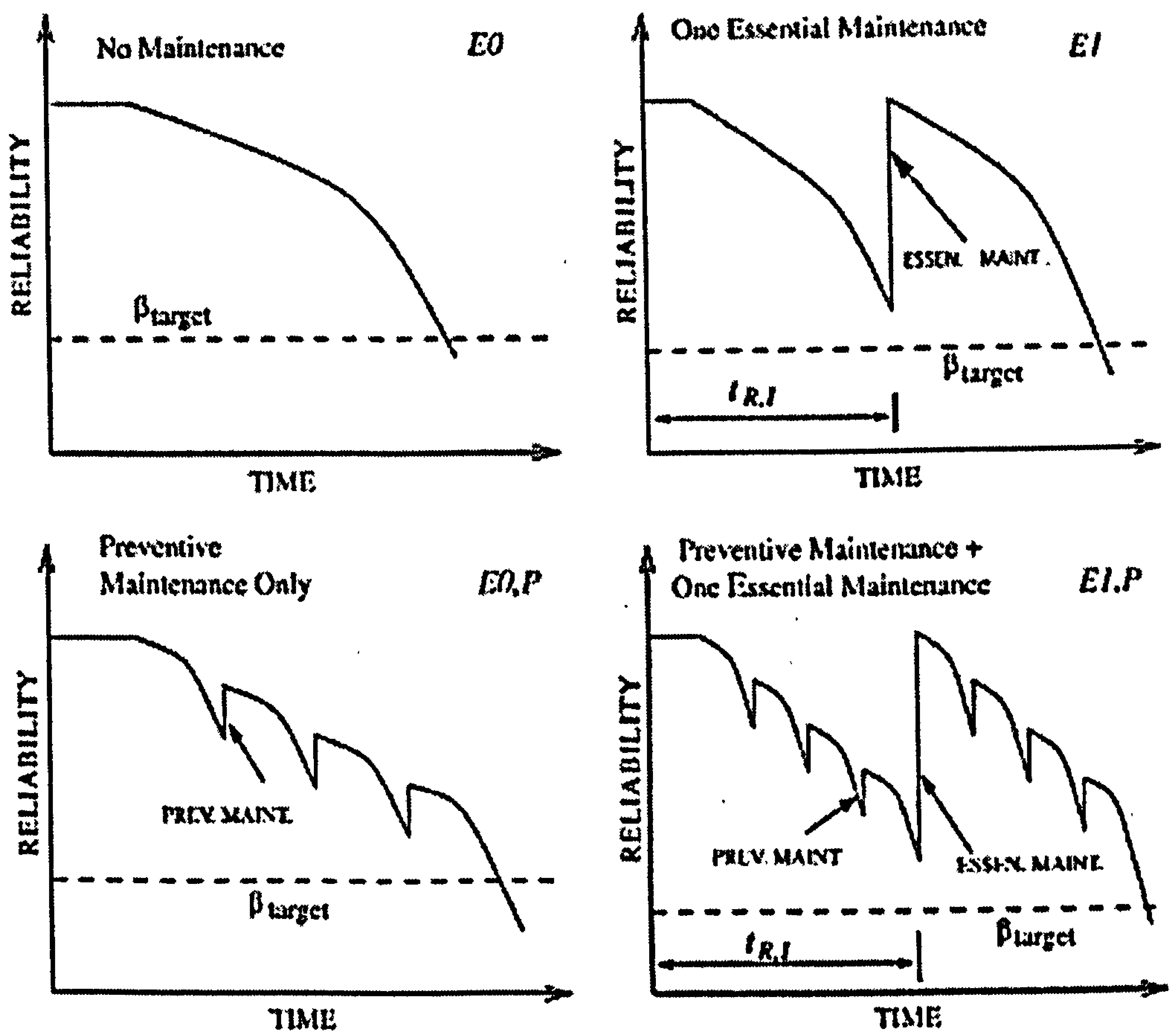


Figure 3.6 Reliability profiles associated with different maintenance plans ([127])

3.3 The uncertainty in the development of maintenance plans

Most of the variables associated with the generation of maintenance plans are uncertain. Therefore, it is required to quantify their uncertainties and evaluate their impact on decision making.

When the effective life concept is considered, the maintenance free life and effective life of maintenance option are the main uncertain variables (Figure 3.4). Rubakantha [64] assigned a truncated lognormal distribution for the maintenance free life of durability options. Likewise, Vassie [76] assumed that the maintenance free life of durability options and effective life of subsequent maintenance options have triangular distributions.

On the other hand, when the reliability index approach is used, eight variables namely β_0, t_I, α, γ, t_{PI}, t_P, t_{PD} and θ are uncertain (Figure 3.5). If several preventative maintenance options are used, additional five uncertain variables per option are added. Some suggestions regarding the probabilistic distributions of these variables can be found in some recent documents. For example, Frangopol [123] used lognormal, uniform and triangular distributions to define these eight variables for shear and bending moment failure modes. Neves [128] assumed that all random variables associated with profiles under no maintenance and five maintenance options have triangular distributions, and their minimum, mode and maximum values are provided by the Highways Agency Report [129].

In general, however, the probabilistic data related to the generation of maintenance plans are very limited, and efforts should be made to quantify the above factors in a probabilistic framework.

Chapter 4

Whole Life Costing

4.1 Principles of whole life costing

4.1.1 Introduction

The Highways Agency documents BD 36/92 [130] and BA 28/92 [131], *Evaluating of maintenance costs in comparing alternative designs for highway structures,* embody the principle of whole life costing (WLC) for highway structures. These documents require that, when considering alternative design options, or options for alterations to existing structures, in addition to the initial costs, future maintenance requirements are also taken into account [132]. In other words, the principle of whole life costing is the recommended tool for choosing between design options for new structures and/or maintenance options for existing structures.

Considering that the effective management of existing bridge structures has become increasingly important, the present study is focused on the costs arising from maintenance activities on existing bridge structures. For this purpose, the basic formula used for whole life costing and the characteristics of relevant variables shall be explained in the following sections.

4.1.2 Basic formula

According to Ryall [88], whole life costing (WLC) is a way of determining the total cost of a bridge structure from its initial conception to the end of its service life. It attempts to quantify, in present monetary terms, the costs arising from all work undertaken on a certain structure. Future costs are converted into their present value (PV) at a given base year using the expression:

$$PV = \frac{C}{(1+r)^t} \quad (4.1)$$

where, C is cost at current price levels; r is the test discount rate (TDR) and t is the time period in years [133]. Alternatively, the term $1/(1+r)^t$ is called the discount factor and determines the discounting ratio between future cost and present value.

In fact, expenditure is spread over the service life of bridge structures, hence the cumulated present value of all expenditures becomes:

$$PV = \sum \frac{C}{(1+r)^t} = \frac{C_1}{(1+r_1)^{t_1}} + \frac{C_2}{(1+r_2)^{t_2}} + \cdots + \frac{C_n}{(1+r_n)^{t_n}} \quad (4.2)$$

4.1.3 Types of costs

The costs to be included for whole life costing of bridge structures would be those arising from following activities:

- design;
- construction;
- inspection;
- maintenance such as repair and upgrading;
- traffic management;
- traffic delays;
- and, possibly, demolition.

The costs for design and construction are initial (capital) costs, whereas inspection cost tends to be spent on a regular basis. Therefore, for the comparison of maintenance options of bridge structure in use, the costs for maintenance, traffic management and traffic delays are important. Among them, the costs for maintenance and traffic management are direct costs which bridge owners should pay for. On the other hand, traffic delay costs are indirect or notional costs which bridge users may lose due to traffic disruption during the bridge maintenance activities.

The difficulty in the application of WLC to existing bridge structures is to collect or calculate reasonable cost data. The direct cost data may be provided using historical data, statistics, and expert opinion where no previous information is given. In 4.1.5, the past literature containing bridge maintenance cost data is reviewed. On the other hand, in the UK, the traffic delay costs can be calculated using special software such as the QUADRO program, and the details of how to calculate traffic delay costs are explained in 4.2.

4.1.4 Discount rate

The discount rate is the value used in accounting procedures to determine the present value of future cash flows arising from a project. The discount rates used by the Department of Transport are usually set by the UK Treasury, and table 4.1 shows the changes in the discount rate from 1978 to 2003. Among the studies undertaken in recent years, some researchers [134] used an 8% discount rate, and others [76, 121, 123, 125] used a 6% discount rate.

Table 4.1 The changes of discount rate

Year	Discount rate
1978-1988	5%
1989-1998	8%
1999-2002	6%
2003-	3.5%

Recently, the Green book [135] recommended that a 3.5% discount rate should be used. Furthermore, for projects with very long-term impacts, over thirty years, a declining schedule of discount rates should be used rather than the standard discount rate. The schedule of long term discount rates is shown in Table 4.2. This discount rate was derived based on the concept of 'Social Time Preference Rate (STPR)'. Here, Social Time Preference is the value society attaches to present, as opposed to future consumption, and the STPR is a rate used for discounting future benefits and costs based on comparisons of utility across different points in time or different generations.

Table 4.2 The declining long term discount rate

Period of years	0-30	31-75	76-125	126-200	201-300	301+
Discount rate	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%

Figure 4.1 shows the variation of discount factors with time when the different discount rates shown in Table 4.1 are applied.

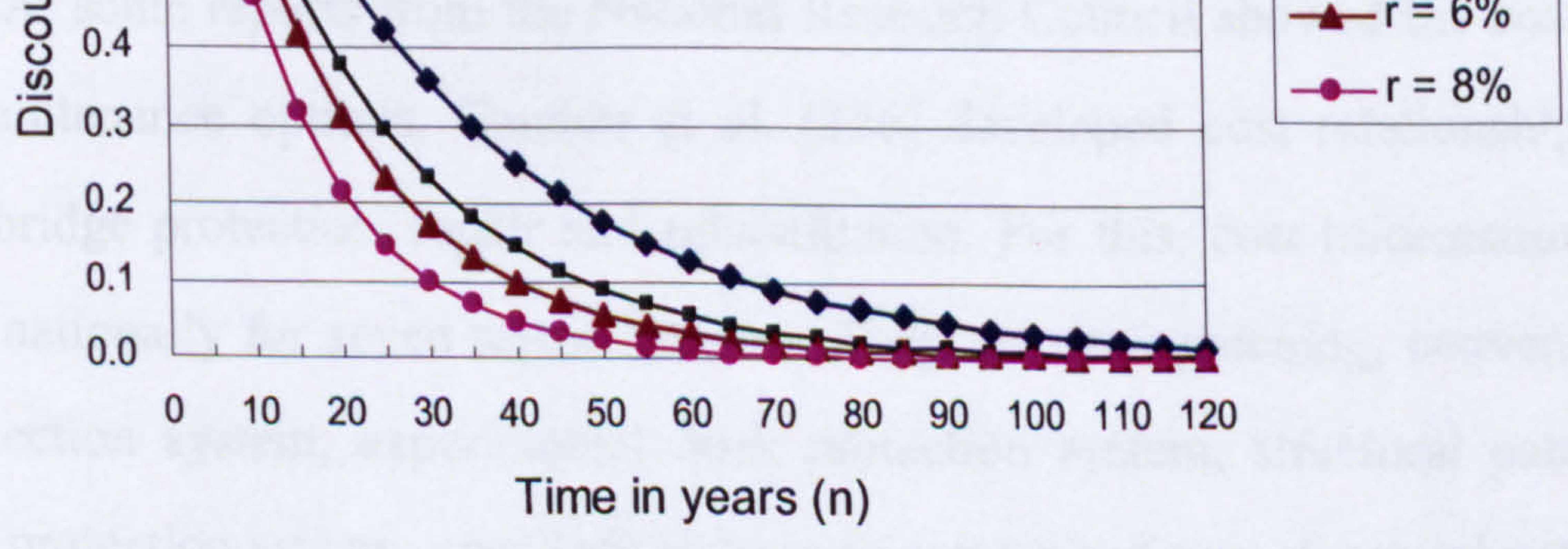


Figure 4.1 Variation of discount factor with time

For discount rates equal to 8%, 6%, 5% and 3.5%, it takes 9, 12, 14 and 20 years respectively for the discount factor to become equal to 0.5, and around 30, 40, 50 and

70 years for the discount factor to become equal to 0.1. This shows that the specification of a discount rate has a great impact on the results of whole life costing. Generally, the lower value of the discount rate, the easier it is to justify higher first costs and lower maintenance costs. On the other hand, higher discount rates would not justify extra durability options included in the initial cost of the bridge in order to reduce future maintenance needs [133].

In summary, the discount rate is a dominant element of WLC, and hence the result of WLC needs to be checked by undertaking a sensitivity analysis for different discount rates. In principle, in this study, the discount rate suggested in the Green book will be used as a benchmark against which other discount rates may be addressed.

4.1.5 Maintenance cost data

A major problem with whole life costing for bridges is the lack of maintenance cost data [132]. Generally, it is difficult to quantify the maintenance cost data because there are huge variations in their values depending on timing, location and other factors. Since the 1990s, some efforts have been made in the USA and UK in order to quantify maintenance cost data. Based on these efforts, past maintenance cost data are summarised in this section.

In the USA, some reports from the National Research Council showed the cost data of the maintenance options. Gannon et al. [136] developed cost relationships for concrete bridge protection, repair and rehabilitation. For this, cost information was collected nationally for seven repair systems. They are deck patching, conventional deck protection system, experimental deck protection system, structural patching, structural protection system, new deck protection system and new structural patching. As a cost model, an inverse power model which has the form of Equation (4.3) was used, and its coefficients were determined by regression against independent variables such as work quantity, contract amount, number of bidders, etc.

$$y = b_1 + b_2 x + \frac{b_3}{x^{b_4}} \qquad (4.3)$$

where, y: dependent variable, predicted natural adjusted cost

x: independent variable, such as work quantity, contract amount, number of bidders, etc.

Weyers et al. [72] applied these models in preparing a repair methods application manual for concrete bridge, and Broomfield [71] also used some of these as approximate cost data for concrete repair methods in the UK. However, the relationships are based on outdated USA data, and it is thus difficult to apply them in the present UK situations.

In the UK, the collection and analysis of bridge maintenance costs was led by the Highways Agency. The Highways Agency appointed Maunsell Ltd and the Transport Research Laboratory to undertake a review of predicted bridge maintenance costs. A review was undertaken during the winter of 1996/1997 and 1997/1998, and a report on *Strategic review of bridge maintenance costs* and its annex were published in 1999 [137, 138]. For this, the Highways Agency's National Structures database (NATS) was analysed to collect data on bridge types, numbers and ages. Bridges were divided into four principal types according to the deck construction material: steel/concrete composite, insitu reinforced concrete, pre-tensioned concrete and post-tensioned concrete. Maintenance costs were estimated for typical overbridges and underbridges of the four main construction types, using information obtained from maintaining agents. For each bridge, two programmes of maintenance were costed: one assuming regular preventive maintenance and the other assuming no maintenance until essential rehabilitation work was required. Costs were calculated as unit costs per m^2 of bridge deck and included traffic management costs. For essential rehabilitation work, bridge deck replacement and significant repairs of the bridge substructures were considered. In a regime of regular preventive maintenance, bridge deck joints, waterproofing, painting, and silane impregnation were included. The traffic delay costs due to maintenance work were also estimated based on some assumptions. Some recent research has relied on this information for their WLC analysis [121, 125].

Another report published by Maunsell Ltd. for the Highways Agency, *Serviceable life of highway structures and their components*, also contained maintenance cost data [139]. These data were collected from maintaining agents, and both their mean and standard deviation values were calculated. Normal distribution was assumed for the cost distribution, in the absence of detailed data leading to an alternative. Table 4.3 shows the recommended distributions of collected data.

Table 4.3 Normal Distributions of Maintenance Cost data (from [139])

Repair	Unit	Mean(£)	Sd (£)	Sample Size
General concrete repairs	m^2	305	220	23
Concrete repairs to slabs	m^2	395	358	4
Concrete repairs to piers/columns	m^2	340	240	9
Parapet repairs	m run	100	55	41
Joints	No	1300	970	46
Joints	m run	150	110	36
Surfacing	m^2	23	11	52
Waterproofing	m^2	23	10	44
Painting	m^2	38	14	8
Bearings	No	130	62	9
Masonry repair	m^2	10.50	2.30	7
Preliminaries	%	25	17	312
Traffic management	%	12	9	66

The values of standard deviation show that there is significant variability in cost data. This is due to many factors such as the availability of local materials, access to the site, the specification of repair and difficulties associated with the works themselves. Therefore, it was stressed that the mean values should be used for the comparisons of whole-life costs, and a summary of the recommended cost data discounted to a common base of April 1998 was presented as shown in Table 4.4.

In 2003, FaberMaunsell Ltd and the Highways agency prepared a draft BD 36, *Application of Whole Life Costs for Design and Maintenance of Highways Structures* [75]. The cost data in this report are considered as being reasonably up-to-date. Table 4.5 shows the summary of cost information in draft BD 36. This table also presents maintenance intervals and works duration rate of maintenance activities.

In Tables 4.4 and 4.5, the maintenance options for which cost data were collected are different except for concrete repairs and cathodic protection options. Therefore it is necessary to use cost data in two tables together in order to determine cost values of all representative maintenance options. However, cost data in Table 4.4 and Table 4.5 were collected in 1998 and 2002, respectively, so all figures in Table 4.4 need to be multiplied by the following price index factor Y in order to be converted into 2002 values.

$$Y = \frac{\text{Retail Price Index in 1st quarter of 2002}}{\text{Retail Price Index in 1st quarter of 1998}} = \frac{173.9}{160.2} = 1.0855 \qquad (4.4)$$

Bridge maintenance cost data have been found in some other documents [129, 140]. However, they are either too old or too limited and are not considered further within this study.

In conclusion, for an effective whole life costing analysis it is very important to collect updated cost data and use it properly. Because of the high variability of cost data, it is preferable to use a probabilistic approach and to produce both mean and upper/lower bound results. This study will use the above cost data in case studies; deterministic as well as probabilistic approaches will be used.

Table 4.4 Summary of Cost Data (from [139])

Repair	Unit	Mean Discounted Cost (£)	Associated Structure Category
Parapet repairs	m	100	Parapet
Joints	m	150	Expansion Joints
Surfacing	m^2	25	All Structural Forms
Waterproofing	m^2	25	Liquid Applied Systems Membrane Waterproofing
Painting	m^2	40	Composite beam, Steel and Aluminium parapets
Bearings	No	130	Bearings
Masonry repair	m^2	10	Masonry Arch
Concrete Repairs			
General Patch repairs	m^2	300	All structural forms except composite beams
Slab repairs	m^2	395	Slab deck, All types of slab
Pier/column repairs	m^2	340	Piers/Column
Concrete replacement	m^2	1940	All structural forms except composite beams
Cathodic Protection			
Install CP system	m^2	185	All structural forms except composite beams
Maintenance of anodes (over 10 years)	m^2	80	
CP Monitoring (over 10 years)	m^2	50	
Silane	m^2	5	Retaining wall, Abutment, Piers, Columns
Concrete Beam Replacement			
Demolition and reconstruction	m^3	2870	RC beam and slab, beams
Temporary support steelwork	m	16750	
Preliminaries	%	25	Add to contract price
Traffic management	%	12	Add to contract price if required

Table 4.5 The maintenance, cost and works data (Adapted from [75])

Maintenance type	Maintenance Interval (years)		Cost of Maintenance (£/m²)	Works Duration Rate (m²/week)
Protective Coating Systems for Steelwork				
Existing structures	15		25	25
Surface tolerant paint system				
New construction structures	20		25	25
Enclosure systems				
GRP Enclosure systems	20		200	500
Concrete Impregnation				
Silane	15		6	1000
Concrete repairs				
Reinforced concrete decks and main members, including substructures	10-60*		300-1200	2-8
Pre-stressed decks and main members	10-60*		600-1200	2-4
Cathodic protection				
Conductive organic coatings	10		50	50
Sprayed zinc	10		100	50
Titanium mesh with cementitious overlay	>30		100	50
Discrete anodes	20		100	50
Expansion joints	Light Traffic Flow	Heavy Traffic Flow	(£/m)	m/week
Buried Joint	15	10	65	60
Asphaltic Plug Joint	10	5	105	50
Nosing Joint	10	5	310	24
Reinforced Elastomeric Joint	11	6	455	26
Elastomeric in metal runners cast in	25	20	650	9
Elastomeric in metal runners resin encapsulated	15	10	415	27
Comb or Tooth Joint	30	25	2200	9

* The maintenance intervals of concrete repairs change according to exposure class and result in different defect area.

4.2 Estimation of traffic delay costs

4.2.1 Introduction

In the comparison of the whole life costs of maintenance plans, the costs to the road user in terms of traffic disruption (known as traffic delay costs) need to be considered. According to BA 28/92 [131], traffic delay costs can be assessed using the DETR computer program QUADRO (Queues And Delays at ROadworks).

QUADRO program uses a simplified network system which has a single main route and a single diversion route (Figure 4.2). The specific network elements required by the program are: the works site; the adjoining sections of main route upstream and downstream of the site, as far as the junctions where diverting traffic is modelled as leaving and rejoining; the next adjacent upstream section on the main route, as far as the next major junction; and the diversion route. Originally, this model was developed mainly for road systems in rural areas, but by converting multiple diversion routes into a single route it can be applied to urban areas, too.

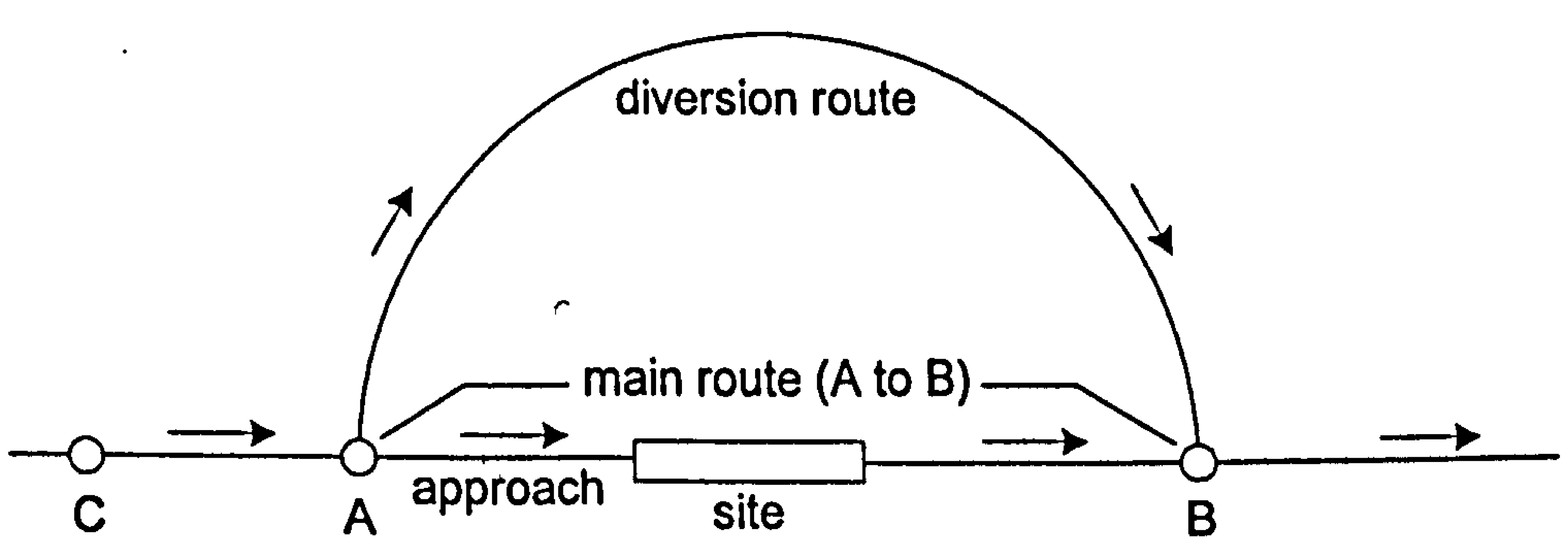


Figure 4.2 Basic elements of the network system used in QUADRO

The QUADRO program requires a number of input data to specify the types of main and diversion route, traffic volume and its mix, works type (traffic management method), etc. Furthermore, the QUADRO program includes a lot of statistical data for costs, accident rates, fuel consumption, vehicle proportions, vehicle occupancy, traffic growth etc. which change with time. The QUADRO program calculates net traffic delay costs as a difference between two cases of without and with site works based on these input data and internal statistical data. The detailed descriptions for all these data are beyond this study's scope, and only important procedures and data shall be explained here. Details can be found in the QUADRO manual [141] and COBA manual [142], though sometimes even these manuals cannot explain the functions of QUADRO program very well.

Generally, traffic delay costs can be many times greater than the direct costs of bridge works. For example, according to reference [137], the traffic delay costs arising from essential maintenance are about ten times greater than the direct engineering costs, and twice the engineering costs for preventive maintenance. Furthermore, reference [75] indicates that where traffic delays are a significant component of the cost of maintenance, they may be used alone in the evaluation of whole life costs for the purpose of comparing alternative strategies for maintenance. Accordingly, considering the importance of including traffic delay costs, this study tried to simplify the QUADRO procedures and develop a subroutine which estimates traffic delay costs. The details are described step by step below.

4.2.2 The types of traffic delay costs

In the QUADRO program, the traffic delay costs are made up of three factors. They are delay time costs, vehicle operating costs and accident costs. These costs vary based on the traffic flows, their speeds and relevant statistical data.

4.2.2.1 Delay time costs

QUADRO calculates the delays at maintenance works and translate these into monetary figures using the standard values of time. The delays at maintenance works are calculated using the General Delay Sub-Model and the Incident Delay Sub-Model. The General Delay Sub-Model calculates time delay from blocking the lanes. On the other hand, the Incident Delay Sub-Model calculates additional time delay from incident such as breakdown and accident. The Incident Delay Sub-Model is an optional model, so this study concentrates on the General Delay Sub-Model. The details of the General Delay Sub-Model are described in 4.2.3.

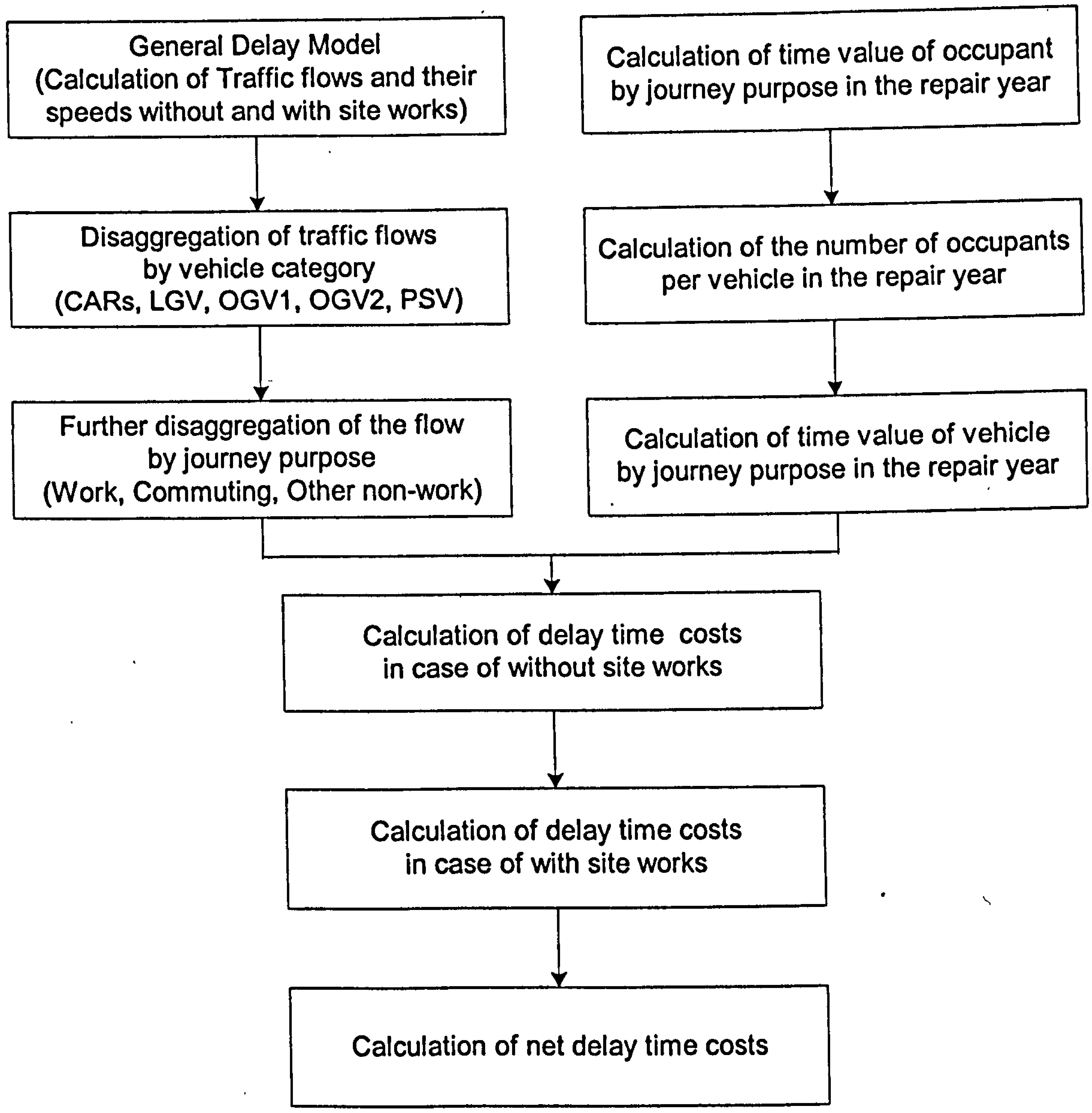


Figure 4.3 Flowchart for calculating delay time costs

Figure 4.3 shows the flowchart for calculating the delay time costs. In order to calculate delay time costs, the total traffic flows are disaggregated by vehicle types (Car/LGV/OGV1/OGV2/PSV) and journey purposes (work/commuting/other non-work). Also, unit time value (pence/hour) of vehicles disaggregated by vehicle types and journey purposes are calculated. By applying the General Delay Sub-Model, journey times of vehicles in cases of without and with site works can be calculated. Then, delay time costs in the cases of without and with site works can be calculated by multiplying the number of disaggregated vehicles, their journey time and unit time value of vehicles, respectively. The net delay time costs can be calculated from the difference of the two cases.

4.2.2.2 Vehicle operating costs

Vehicle Operating Cost (VOC) in QUADRO comprises six items: fuel, oil, tyres, maintenance, depreciation, and size of vehicle fleets. Only items that vary with the use of the vehicle are measured.

The resource cost of fuel consumption is estimated using a parabolic function of the form:

$$C=a+bV+cV^2 \tag{4.5}$$

where, C = cost in pence per kilometre per vehicle;

V = average link speed in kilometres per hour;

a, b, and c are parameters defined for each vehicle category.

On the other hand, the non-fuel elements of the marginal resource cost are combined in a hyperbolic function of the form:

$$C = a1 + b1/V \tag{4.6}$$

where, C, V, a and b are defined as above.

The VOC formulae parameter values in 2002 prices by type of vehicle are given in Table 4.6 and corresponding graphs are illustrated in Figure 4.4. Application of these parameters calculates the cost in pence per kilometre.

From Figure 4.4, the most efficient vehicle speeds for resource cost of fuel consumption are between 60 and 70km/h. If the vehicle speeds are very fast or very slow, then the resource cost of fuel consumption will increase. On the other hand, the formulas for the non-fuel elements of the marginal resource cost have a hyperbolic shape, and the cost will decrease as the vehicle speeds increase.

Table 4.6 VOC Formulae 2002 Parameter Values in pence/km (2002 prices)

Category	Fuel			Non-Vehicle Fuel	
	a	b	c	a1	b1
Car	2.648	-0.0465	0.000325	3.308	19.048
LGV	3.953	-0.0695	0.000540	5.910	33.970
OGV1	10.481	-0.1772	0.001431	5.501	216.165
OGV2	24.105	-0.3794	0.003000	10.702	416.672
PSV	11.537	-0.2121	0.001714	24.959	569.094

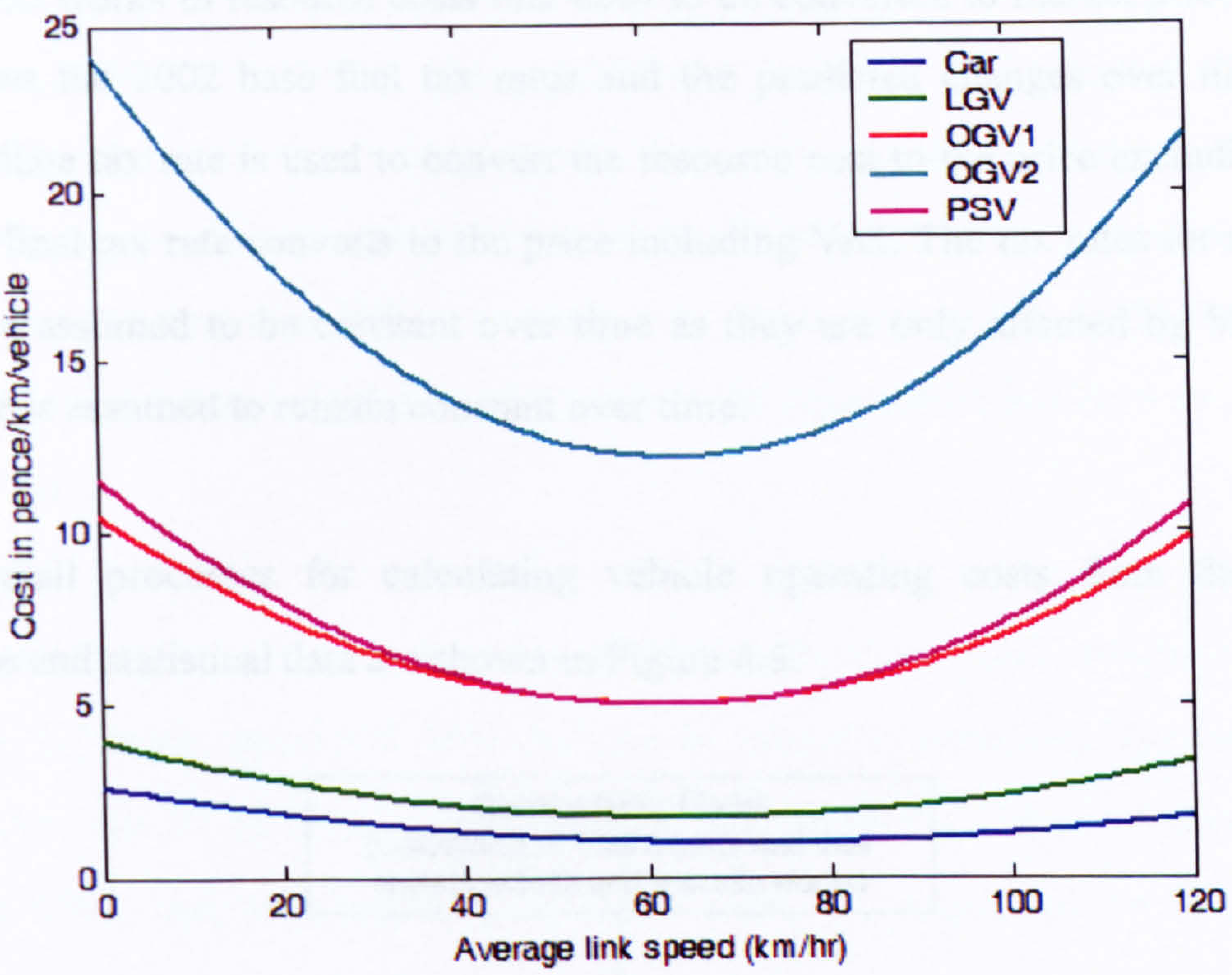
QUADRO adjusts the values of the fuel cost parameters a, b and c over time. This reflects changes in the price of fuel and also the fuel efficiency of vehicles. For cars it also reflects the changes in the proportion of the vehicle fleet using either petrol or diesel. The annual percentage growth rates in fuel resource costs per vehicle kilometer are given in Table 4.7.

Table 4.7 Compound Annual Growth Rates (%) in Fuel Costs

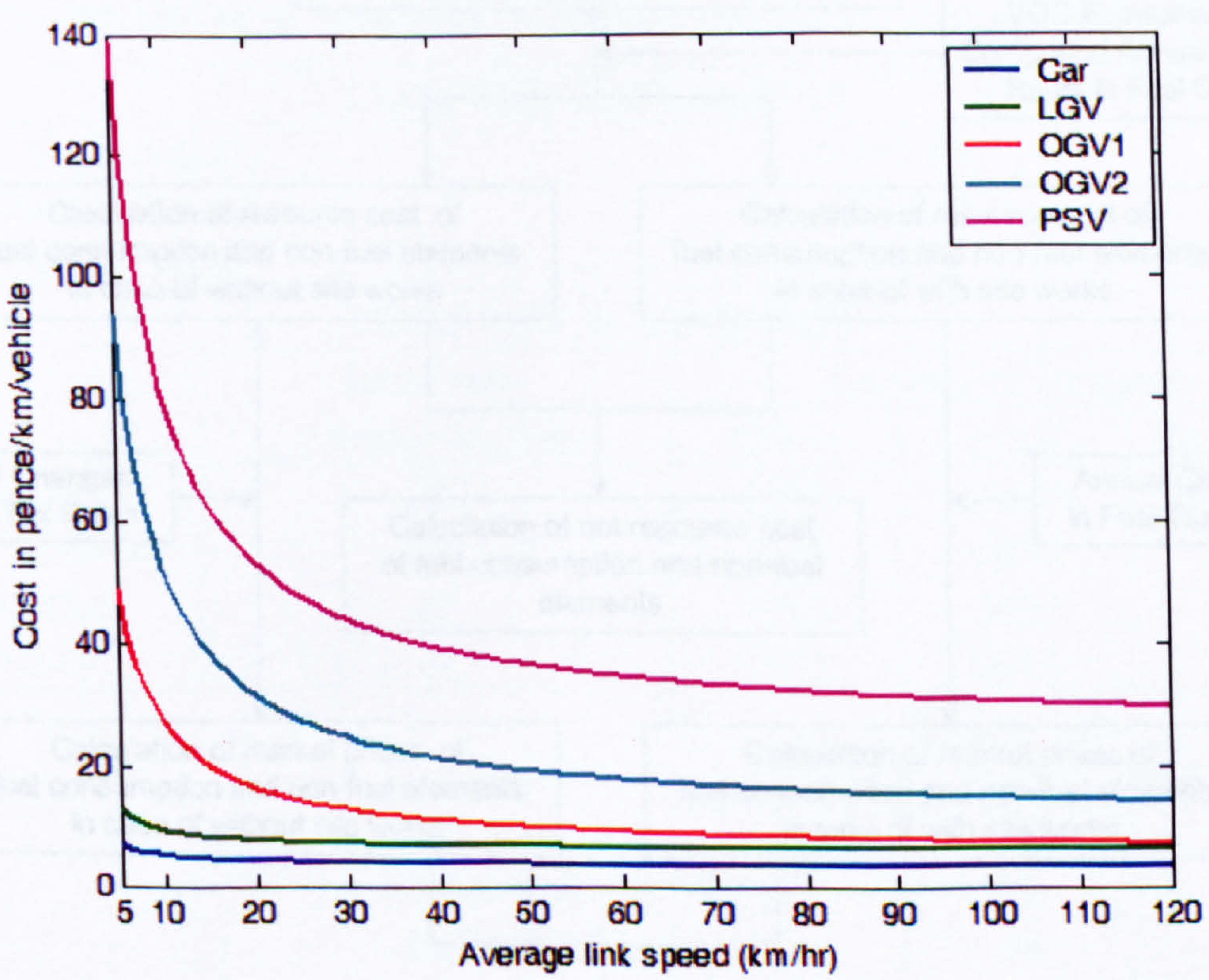
Years	Vehicle Type				
	Cars % pa	LGV % pa	OGV1 % pa	OGV2 % pa	PSV % pa
2002 – 2003	5.52	5.23	6.08	6.08	7.15
2003 – 2010	-4.21	-2.44	-2.16	-2.16	-1.17
2010 – 2031	-0.54	0	0	0	0
2031 – 2099	0	0	0	0	0

Table 4.8 Annual Changes in Fuel Tax Rates (%)

Range of Years	Vehicle Type			
	Cars		LGV/OGV/PSV	
	Intermediate	Final	Intermediate	Final
2002 Base Tax Rates	277%	345%	249%	310%
Annual Changes (% pa)				
2002 - 2003	-8.51	-8.13	-6.06	-5.72
2003 - 2004	-0.14	-0.13	0.40	0.38
2004 - 2005	6.30	5.95	6.30	5.92
2005 - 2006	5.62	5.33	5.62	5.31
2006 - 2007	2.25	2.15	2.25	2.13
2007 – 2099	0.00	0.00	0.00	0.00



(a) Resource cost of fuel consumption



(b) Resource cost of non-fuel elements

Figure 4.4 Variation of vehicle operating costs with average link speed

QUADRO works in resource costs that need to be converted to market prices. Table 4.8 shows the 2002 base fuel tax rates and the predicted changes over time. The intermediate tax rate is used to convert the resource cost to the price excluding VAT and the final tax rate converts to the price including VAT. The tax rates for non-fuel VOC are assumed to be constant over time as they are only affected by VAT. The VAT rate is assumed to remain constant over time.

The overall processes for calculating vehicle operating costs from the above formulae and statistical data are shown in Figure 4.5.

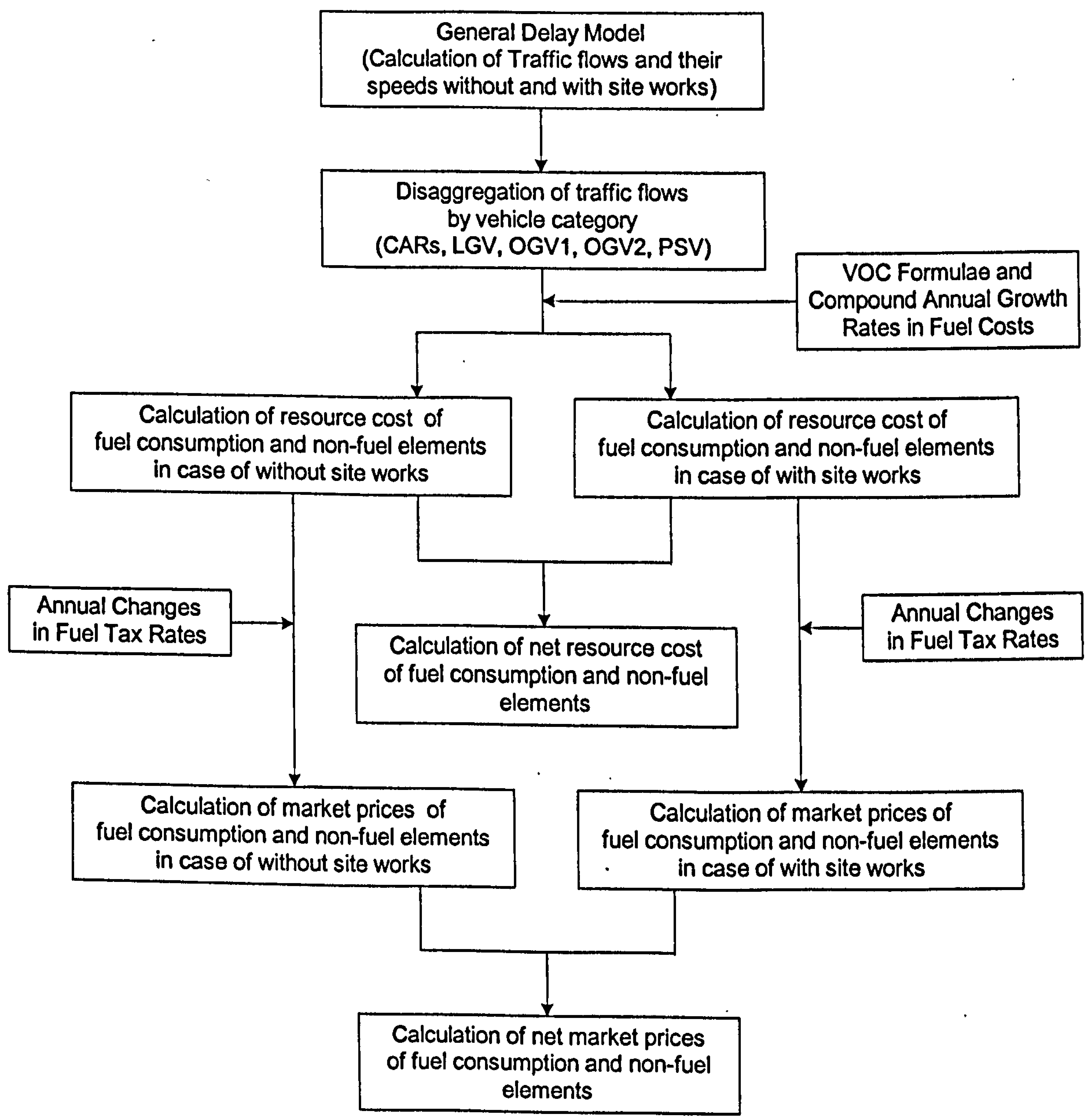


Figure 4.5 Flowchart for calculating Vehicle Operating Costs

4.2.2.3 Accident costs

When road works are taking place, additional accidents are expected. There is evidence that the accident rate increases on the section of road affected by the works, and traffic diverted from the main route may travel on roads of a lower standard, thus both factors leading to a higher accident rate. Furthermore, the likelihood of the diversion route being longer than the main route may also contribute to a higher accident rate.

The accident costs in QUADRO consist of (1) casualty costs (fatal, serious and slight injuries), (2) costs associated with damage to property, insurance administration, police time, and (3) an allowance for damage only accidents. Table 4.9 shows these costs in 2002, and accident costs in other years are calculated by considering assumed compound annual rates of growth of accident values.

Table 4.9 Components of Accident Costs (2002 values and prices) (from [142])

COST PER CASUALTY, £				
Fatal casualty	1,249,890			
Serious casualty	140,450			
Slight casualty	10,830			
COST PER ACCIDENT, £				
	Insurance Administration	**Damage to Property**		
		Urban	Rural	Motorway
Fatal accident	230	5977	10136	12894
Serious accident	143	3203	4620	11002
Slight accident	87	1890	3063	5566
Damage only	42	1352	2019	1941
		Police Cost		
		Urban	Rural	Motorway
Fatal accident		1463	1387	2030
Serious accident		122	341	320
Slight accident		44	44	44
Damage only		3	3	3
Number of Damage Only Accidents per PIA		17.7	7.8	7.6

QUADRO calculates and sums up these three cost components per average personal injury accident (PIA) on various types of road by using following relations:

(1) Casualty costs

$= NC_f \times CC_f + NC_{se} \times CC_{se} + NC_{sl} \times CC_{sl}$ where,

NC_f, NC_{se}, NC_{sl} : Average number of fatal, serious and slight casualty per PIA, respectively

CC_f, CC_{se}, CC_{sl} : Costs per fatal, serious and slight casualty, respectively

(2) Costs related to damage to property, insurance administration, police time

$= AP_f \times (I_f + D_f + P_f) + AP_{se} \times (I_{se} + D_{se} + P_{se}) + AP_{sl} \times (I_{sl} + D_{sl} + P_{sl})$ where,

AP_f, AP_{se}, AP_{sl} : Proportions of fatal, serious and slight accident, respectively

$(AP_f + AP_{se} + AP_{sl} = 1.0)$

I_f, I_{se}, I_{sl} : Insurance administration costs of fatal, serious and slight accident, respectively

D_f, D_{se}, D_{sl} : Damage to property costs of fatal, serious and slight accident, respectively

P_f, P_{se}, P_{sl} : Police costs of fatal, serious and slight accident, respectively

3) An allowance for damage only accidents

$= N_{do} \times (I_{do} + D_{do} + P_{do})$ where,

N_{do} : Number of damage only accidents per PIA

I_{do}, D_{do}, P_{do} : Insurance administration cost, damage to property cost and police cost per damage only accident, respectively

Total numbers of PIA with/without site works on main and diversion route are calculated by considering accident rates of corresponding accident types. Total accident costs with/without site works are calculated by multiplying total numbers of PIA with/without site works and accident costs per PIA, and then net accident costs are calculated by determining the difference between total accident costs with and without site works.

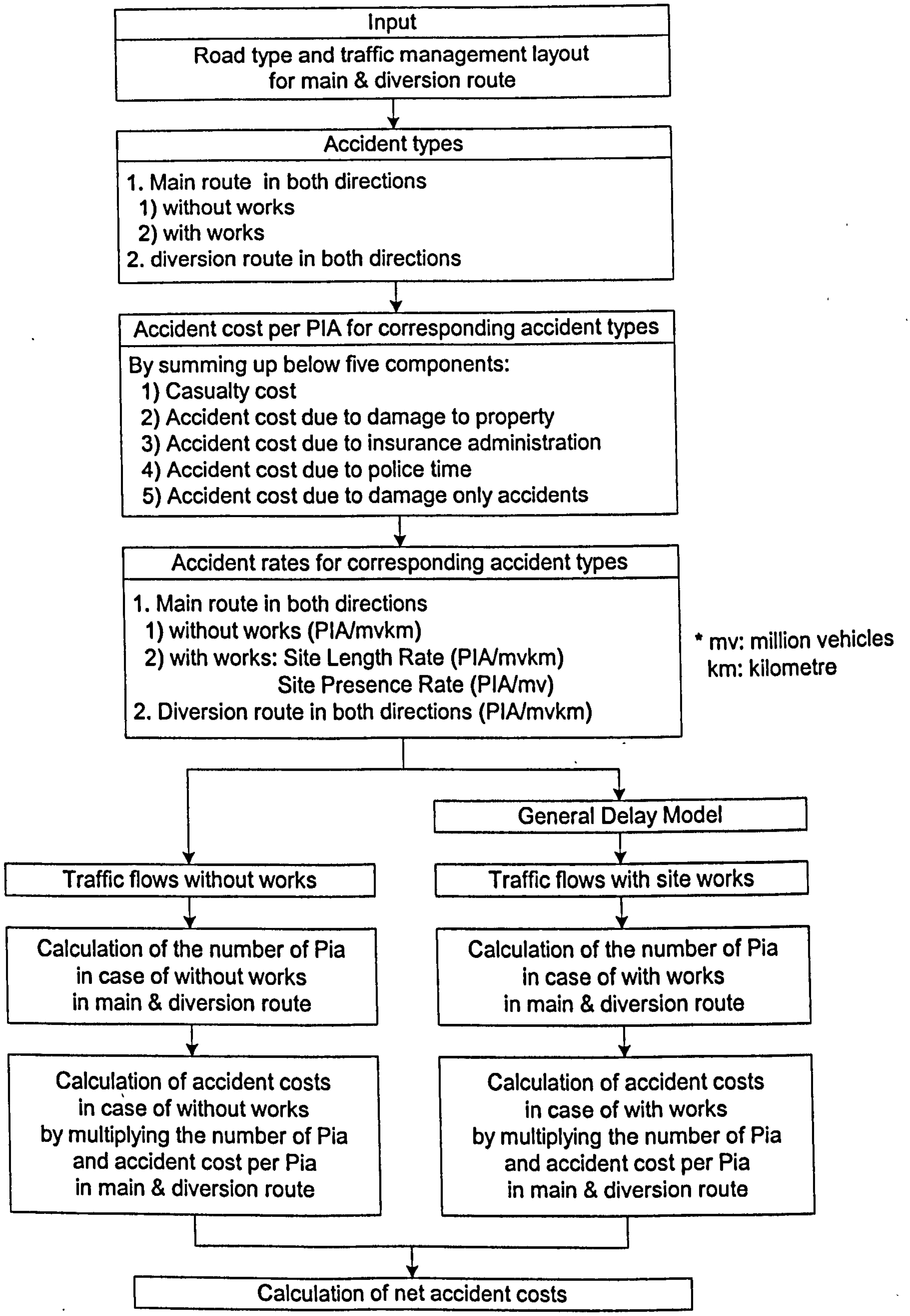


Figure 4.6 Flowchart for calculation of accident costs

Figure 4.6 shows the flowchart for the calculation of net accident costs. Further descriptions and relevant statistical data for all these processes can be found in the QUADRO manual [141].

However, it may be useful to explain two types of accident rates associated with works site here. The accidents associated with works site are split into two components. The first corresponds to accidents along the site itself, reflecting a change in the geometric standards of the carriageway and possibly where the direction of travel is affected by any crossover. The number of accidents is dependent on the flow, the site length, and the rate, known as the *Site Length Rate.* The second component is made up largely of accidents in the approaches to and departures from the site. These are independent of the site length and are calculated using the flow through the site and a rate expressed in PIA per million vehicles, which is a measure of the extra accidents associated with the presence of these site features. This second rate is referred to as the *Site Presence Rate.*

In summary, the traffic delay costs are calculated by summing up delay time costs, vehicle operating costs and accident costs as explained above. The cost values vary significantly depending on input data, used assumptions and maintenance time. Table 4.10 presents the annual average values of traffic delay costs per person and per vehicle in 2002. This table is useful in grasping the overall scale of traffic delay costs.

4.2.3 General Delay Sub-Model

4.2.3.1 Background theory

The General Delay Sub-Model is the basic modelling component which calculates queue lengths and diverted flows in the network system. This sub-model is used 14 times, once in each direction of travel, for each day of the week. Within the sub-model, each hour of the day is modelled in turn, with the traffic conditions at the end of each hour (specifically, the queue length) being carried forward to the next hour.

The underlying assumption of the sub-model is that the drivers' objective is to minimise journey times. Hence, the following expression gives the limiting condition beyond which traffic on the main route will seek an alternative route.

Journey time via main route (including any queuing delay) (on average)
= Journey time via diversion route

Table 4.10 Annual Average Values of Time per Person and per Vehicle in COBA based on 2000 occupancies (2002 values and resource prices)

Type of Vehicle and Purpose	Weekly Average Occupancy	Occupant Purpose	Value of time (pence/hour)	
			per occupant	per vehicle
Working Car	1.00 driver 0.20 passengers	Working Working (Average)	2186 1566 (2083)	2499
Non-working Car **- Commuting** **- Other**	 1.00 driver 0.14 passengers 1.00 driver 0.85 passengers	 Commuting Commuting Other Non-Work Other Non-Work	 417 417 368 368	 475 475
Average Car	1.00 driver 0.68 passengers	(Derived from above assuming 13.1% of car kilometres are in 'working' mode, 25.3% in 'commuting' mode and 61.6% in 'other' mode)		867
Working Light Goods Vehicle (LGV)	1.00 driver 0.20 passengers	Working Working	842 842	1010
Non-working LGV **- Commuting** **- Other**	 1.00 driver 0.59 passengers 1.00 driver 0.59 passengers	 Commuting Commuting Other Non-Work Other Non-Work	 417 417 368 368	 663 585
Average LGV	1.00 driver 0.20 passengers	(Derived from above assuming 88% of LGV kilometres are in 'working' mode, 2.6% in 'commuting' mode and 9.4% in 'other' mode)		961
OGV1&OGV2	1.00 driver	Working	842	842
Public Service Vehicle (PSV)	1.00 driver 0.20 passengers	Working } Working (2.9%) (Ave working occupant) } Commuting (20.5%) } Other (76.6%)	842 1672 (1059) 417 368	5916
Average Vehicle	Based on 2002 national average vehicle proportions and 2002 occupancies)			930

In order to determine the queue length and diverted flow, it is necessary to understand two types of queue called 'Equilibrium' and 'Actual' queue.

'Equilibrium queue' is defined as "that queue on the main route which for a given demand of flow on the diversion route and main route will make the journey time on the main route equal to the journey time on the diversion route" [141]. The equilibrium queue is variable, depending on the characteristics of the diversion route and the level(s) of demand flow on the mainline and diversion routes.

The Equilibrium queue can be calculated by comparing the journey time on the diversion route with that on the main route. The journey time on the main route includes the time spent queuing on the approach as well as the time to pass through the works site and reach the end of the section downstream of the site.

On the other hand, the 'actual queue' is a function of demand flow through the works site and the site capacity. For example, when demand exceeds capacity a queue will grow, when demand equals capacity a queue will remain constant and when capacity exceeds demand there will be either no queuing or queue will disperse. Figure 4.7 shows the development of a queue within a time period of constant demand and capacity. The development of a queue is a function of how many vehicles divert.

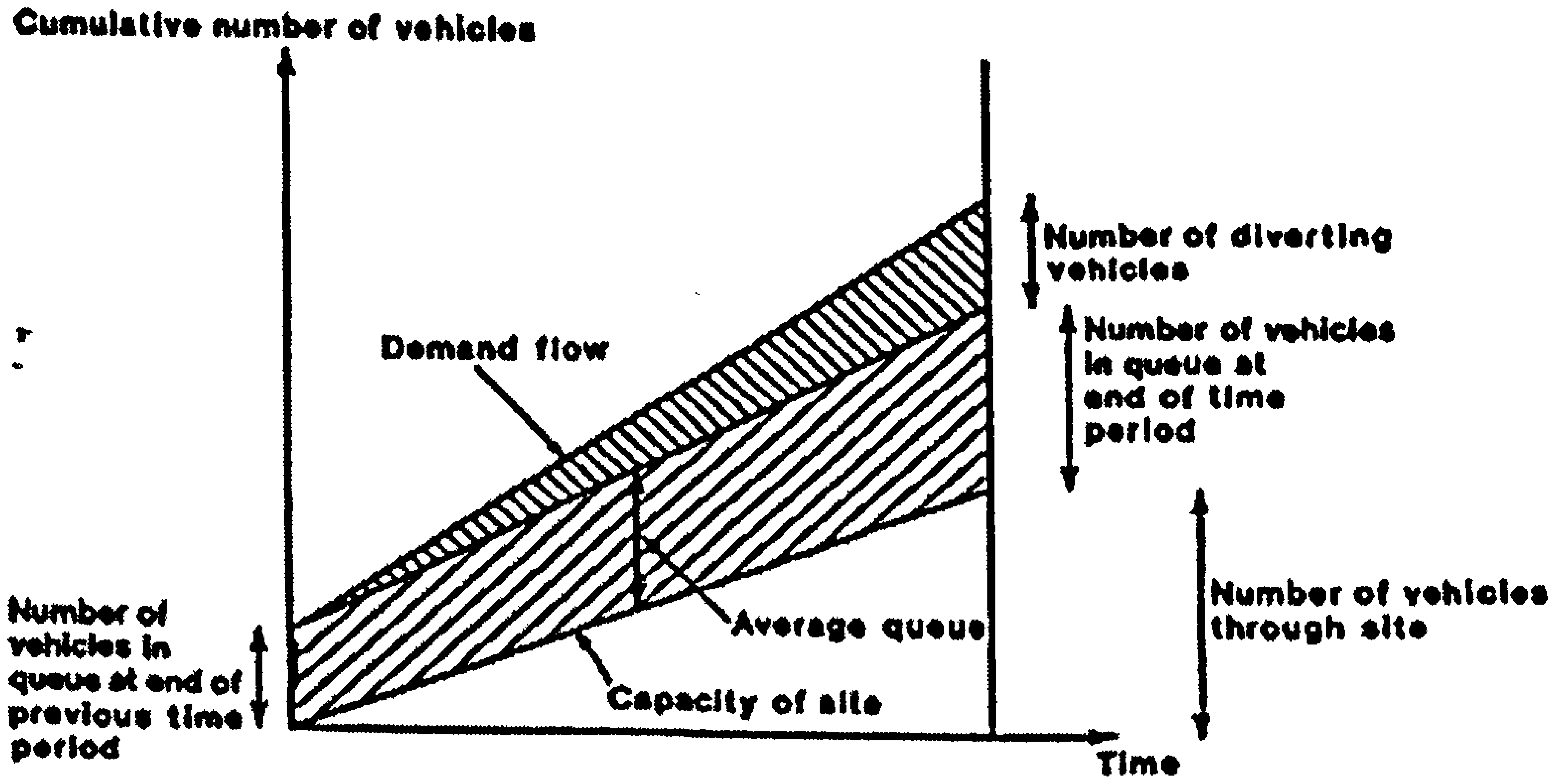


Figure 4.7 Development of a Queue ([141])

The QUADRO program assumes diversion takes place according to Figure 4.8 below. Curve A describes the possible variations in the average queue length as a function of the number of diverting vehicles varying between 'nothing divert' and 'everything diverts'. Curve A is defined by deterministic queuing theory applied as illustrated in Figure 4.7. On the other hand, Curve E describes the equilibrium queue length as a function of the number of vehicles diverting, and the intersection of the two curves determines the amount of traffic diverting and in turn the queue length.

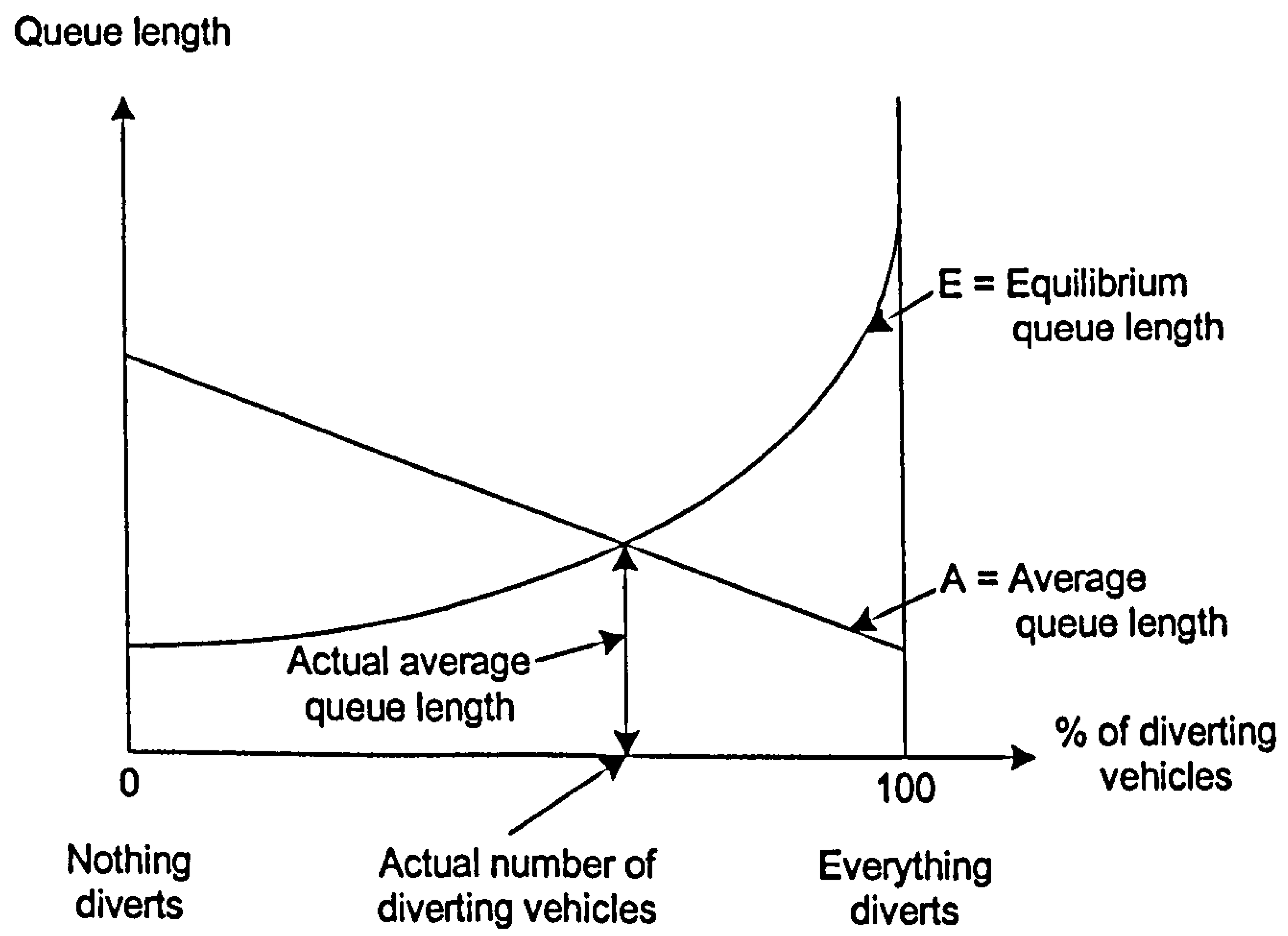


Figure 4.8 Method of determining queue length and number of vehicles diverting

The time basis for average queue length, speeds etc is 1 hour. The QUADRO program calculates queue length and number of vehicles diverting in half hourly intervals in order to smooth flows between hours. At the end of each hourly interval the weighted averages of number of vehicles, capacity and speeds are produced and costed.

However, in this study, a time basis of 1 hour is used without splitting into half hourly intervals, because the factors used for traffic splitting in the QUADRO program are considered to be arbitrary.

4.2.3.2 Quantification of the General Delay Model

The purpose of the General Delay Model is to find the diverting flow and queuing distance, and thus the resulting flow in the main and diversion route. It can be done by calculating the intersection point between curves A and E in Figure 4.8. The procedure to find the intersection point is described below.

1) At the beginning of each time, the demanding flow in main route (DF), normal flow in diversion route (NF) and start queue (Qi) are given as a result of traffic splitting and previous application of the General Delay Model.

2) As a first iteration to find the intersection point, two extreme traffic diverting cases, i.e. everything diverts (case 1) and no traffic diverts (case 2), are assumed. For each case, diverting flow (FDIV), flow on main route (FMAIN), and total flow on diversion route (TFDIV) are calculated using following relations.

(1) Assuming everything diverts: FDIV1=DF, TFDIV1=DF+NF, FMAIN1=Qi

(2) Assuming no traffic diverts: FDIV2=0, TFDIV2=NF, FMAIN2=DF+Qi

3) Then, equilibrium queue (QR), actual queue (QD) and the traffic intensity in the main route (ρ) for two cases, i.e. QR1, QD1 and $\rho 1$ for everything diverts and QR2, QD2 and $\rho 2$ for no traffic diverts, are calculated based on following formulas.

(1) Equilibrium queue (QR)

QR = (Diversion Journey Time - TA – TS – TD) / Spd_Div

where, Diversion Journey Time = Diversion Distance/Speed On Diversion Route

TA = travel time on approach to site

TS = travel time through site

TD = travel time downstream of site

and Spd_Div = difference between time taken to travel 1m when travelling at Vq and Va (where Vq is speed through queue and Va is speed on approach to site)

i.e. Spd_Div = 1/Vq – 1/Va

(2) Actual queue (QD)

Actual queue (QD) = Flow on main route – Main route capacity

If QD is less than 0, QD = 0.

(3) Traffic intensity

Traffic intensity (ρ) = Flow on Main route / Main route capacity

4) From the values in 3), traffic intensity at the intersection point (ρ_x) is calculated using the following relations.

(1) If QR1>QD1 and QR2>QD2, then $\rho_x = \rho 2$;

(2) If QR1<QD1 and QR2<QD2, then $\rho_x = \rho 1$;

(3) In other cases, $\rho_X = \rho 1 + (\rho 2 - \rho 1) \times \frac{|QD1 - QR1|}{|QD1 - QR1| + |QR2 - QD2|}$.

5) If $\rho_x = \rho 1$ or $\rho_x = \rho 2$ within a certain tolerance (here, 0.001), then solution has been found with the following results and the iteration is stopped.

(1) If $|\rho 1 - \rho_X| < 0.001$, then FDIV=FDIV1, QD=QD1, FMAIN=FMAIN1

(2) If $|\rho 2 - \rho_X| < 0.001$, then FDIV=FDIV2, QD=QD2, FMAIN=FMAIN2

6) If the solution cannot be found in 5), new traffic flows in the main route and diversion route are calculated assuming 'partial traffic diverts' using the following relations. Additionally, corresponding Equilibrium queue (QRx) and Actual queue (QDx) are calculated using the relations in 3).

FDIVx = DF + Qi - $\rho_x \times$ Main route capacity

$FMAINx = \rho_x \times$ Main route capacity

$TFDIVx = NF + FDIVx$

7) Then, above 'partial traffic diverts' case replaces one of the two extreme traffic diverting cases in 2) under the following condition:

(1) If (QR1-QD1)×(QRx-QDx) < 0, then

ρ2= ρx, QR2=QRx, QD2=QDx, FDIV2=FDIVx, FMAIN2=FMAINx

(2) If (QR1-QD1)×(QRx-QDx) > 0, then

ρ1= ρx, QR1=QRx, QD1=QDx, FDIV1=FDIVx, FMAIN1=FMAINx

8) Then, steps 4) ~ 7) are repeated until the solution has been found.

4.3 Uncertainty in WLC

The trend towards a probabilistic approach in whole life costing of bridge maintenance options in the UK began in the mid-1990s mainly by Vassie [76, 134] and Rubakantha [64, 65, 143]. The main reason for the use of a probabilistic approach is that most of the input data for whole life costing are uncertain due to difficulties in forecasting and variability of data itself. According to Rubakantha [143], the advantage of the probabilistic approach is that it enables us to compare the options in the presence of inherent data uncertainties rather than constantly searching for more accurate data.

Figure 4.9 shows the schematic representation of whole life costing based on probabilistic inputs. The maintenance timing is based on a prediction of future performance of bridge structures, so it includes the uncertainty related to forecasting. On the other hand, the uncertainty in maintenance costs stems mainly from the variability of the data itself as already discussed in 4.1.5.

The uncertainties in determining maintenance timing were considered in Chapter 3, so in this section, the remaining random variables related to whole life costing and the main tools for dealing with uncertainty will be critically reviewed through past research efforts.

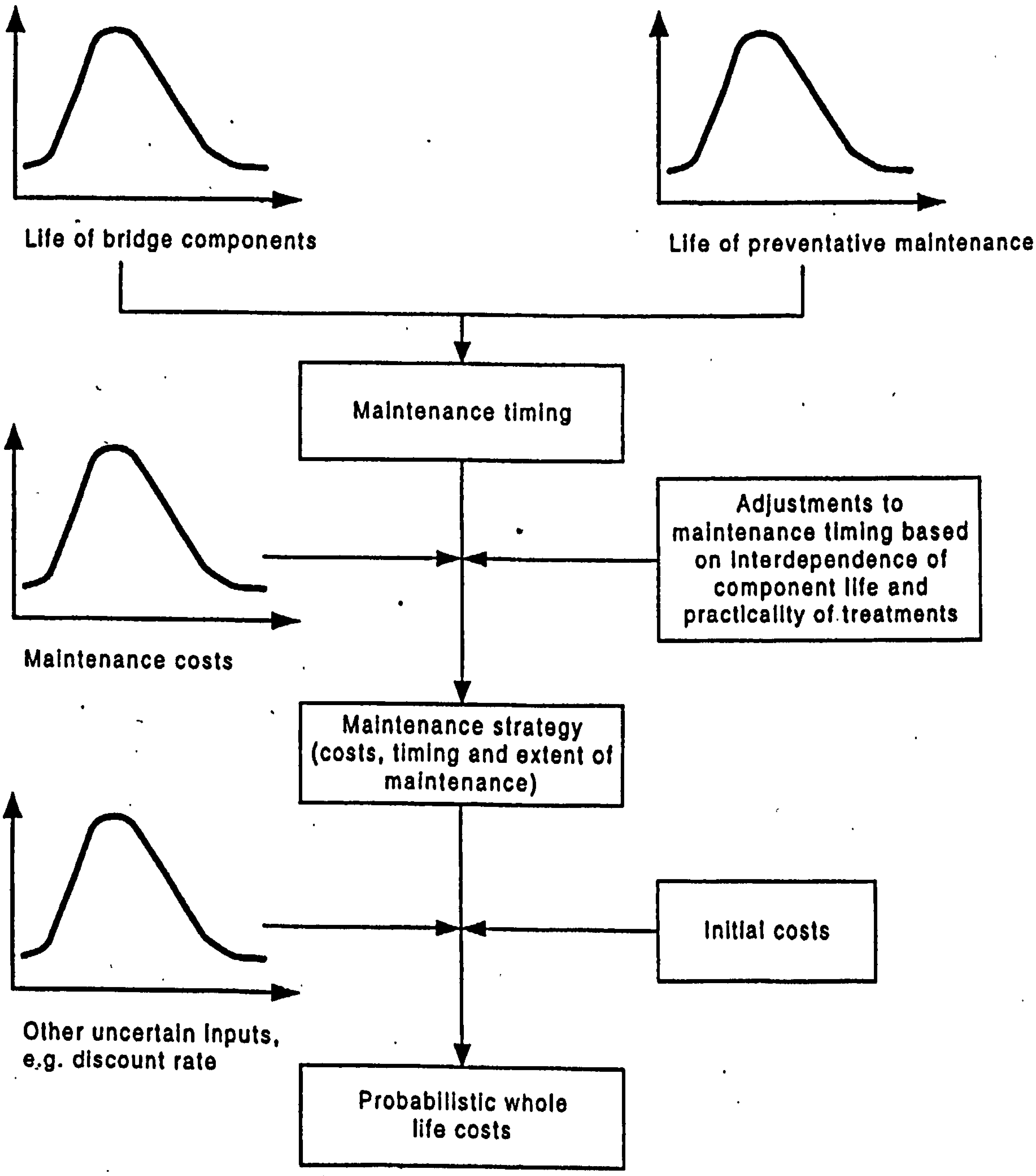


Figure 4.9 Whole life costing based on probabilistic inputs [143]

Random variables

A prerequisite for probabilistic analysis is to identify the important random variables and obtain a feel for their distributions. Table 4.11 presents random variables related to whole life costing analysis of bridge maintenance and their respective distribution shapes according to four past studies [64, 76, 129, 139].

The common random variables used in different studies are serviceable life of bridge structures or effective life of maintenance options, costs, and initial traffic flows. The distribution shapes of these three variables were derived from data collecting, fitting techniques and/or simple assumptions. Generally, when the data are limited, triangular or normal distributions were assumed and otherwise curve fitting techniques were used. From the distribution shapes shown in Table 4.11, it is difficult to say that each random variable can be represented by a single distribution shape without exception. Therefore, it is necessary to decide proper distribution shapes from collected data or based on reasonable expert opinions.

The traffic growth rates and discount rates were also assumed as random variables in Vassie's and Rubakantha's studies, respectively. However, the Green book [135] recommended that fixed discount rates should be used for whole life costing analysis of bridge structures. Likewise, the values of future traffic growth rates were suggested in QUADRO program [141]. Therefore, it is considered to be more reasonable to use fixed values for traffic growth rates and discount rates based on these documents.

Table 4.11 Random variables and their distribution shapes

	Vassie (1999) [76]	Maunsell Ltd (1999) [139]	Rubakantha (2001) [64]	Parsons Brinckerhoff Ltd (2004) [129]
Serviceable life (Effective life)	Triangular	Weibull	TLognormal*	Triangular
Costs	F	Normal	F	Triangular
Initial traffic flows	Lognormal2	NC	Lognormal2	NC
Traffic growth rates	TNormal*	NC	F	NC
Discount rates	F	F	TNormal*	NC

*T: Truncated **F: Fixed value ***NC: Not considered in the study

Main tools

In principle, there are many ways to quantify the effects of uncertainty on the whole life costing analysis of bridge options. In practice, past researches have focused on sensitivity analysis, in some cases coupled with crude Monte Carlo simulation.

Deterministic sensitivity analysis is used to identify which inputs produce highest sensitivity with regard to outputs. For instance, Rubakantha [65] showed that the uncertainties in maintenance free life, traffic flow and discount rate have significant effects on the evaluated whole life cost by executing regression analysis between input and output values. However, as well known, sensitivity analysis cannot explain the effects when the random variables change simultaneously.

Therefore, probabilistic analysis based on Monte Carlo simulation was used. Examples can be found in research undertaken by Rubakantha [64, 143], Vassie [76, 134], and Neves [128], etc. The implementation of Monte Carlo simulation to the present study will be explained in Chapter 6.

4.4 The application of WLC to this study

The fundamentals of whole life costing and its applicability to bridge maintenance have been reviewed in this chapter. The principles of whole life costing are relatively simple and straightforward, but the actual implementation is not so easy because there are many variables to be included and relevant data are not well established.

In particular, the processes for calculating traffic delay costs are quite complex. Therefore, if there are many maintenance plans to be compared with each other and if each maintenance plan is composed of several maintenance actions to be undertaken at different future times, appraisal through whole life costing could become an unduly complex task. As a simplified way of calculating traffic delay costs, Rubakantha [64] used QUADRO reckoner tables which can be found in MCHW Volume 1 Annex 5.5.2 [144]. However, the traffic delay cost values found therein are based on several assumptions and pertain to only few representative cases, so it is difficult to adopt these tables for different situations. Furthermore, the cost values in these tables are by now outdated. Therefore, it was decided not to use QUADRO reckoner tables in the present study.

Thus, bearing in mind the procedures followed in previous work, this study aims to improve the following two key aspects:

1) In order to enable calculation of traffic delay costs of a wide range of maintenance plans, a computer code which calculates traffic delay costs based on principles and data used in QUADRO 4 program is developed. For this purpose, the QUADRO manual was carefully reviewed and details which could not be found therein were obtained from the Transport Research Laboratory [145]. The results of traffic delay costs from the computer code were compared with those obtained from the QUADRO program. However, the QUADRO program is quite complex and the computer code is confidential, so it was impossible to embody all the characteristics of the QUADRO program. Accordingly, the computer code developed in this study is a simplified form of the QUADRO program and has the following characteristics.

(1) A number of default values which were determined mainly based on nationally collected statistical data are fixed as constant values in order to minimise input data. In the QUADRO program, they can be changed if corresponding local data are available.

(2) Delay time costs from the Incident Delay Sub-Model which is an optional model in the QUADRO program are not included in this study. However, their values are less than 2% of delay time costs from the General Delay Sub-Model, so its exclusion makes very little difference.

(3) In the QUADRO program, 11 kinds of road classes can be specified in order

to define different speed/flow relationship in the main route. Among them, former six road classes for rural roads and motorways are programmed in the present study, and another five road classes for urban/small town/suburban road are excluded. This makes it possible to reduce input data requirement for defining speed/flow relationship in urban/small town/suburban roads. Furthermore, the fact that the QUADRO program was originally developed for rural road/motorway was also taken into account.

(4) In this study, a time basis of 1 hour is used for traffic splitting. On the other hand, the QUADRO program used half hourly intervals in order to smooth flows between hours.

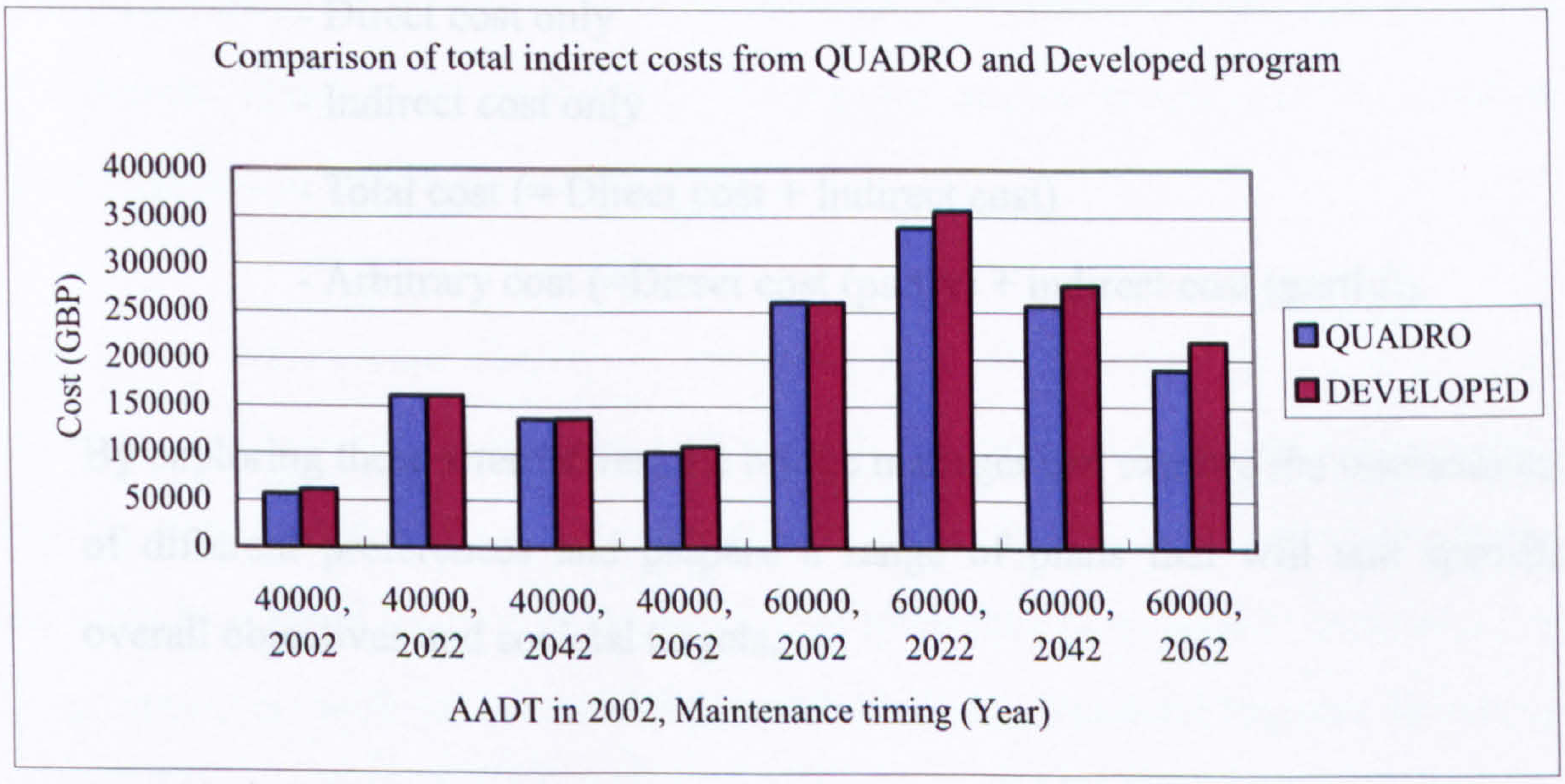


Figure 4.10 Comparison of traffic delay costs from the QUADRO program and the developed computer code

Figure 4.10 presents the comparison of traffic delay costs from the QUADRO program and the computer code developed in the present study for eight cases which have been formed by combining two types of AADT (40,000 and 60,000) on the main route in 2002 and four different maintenance timings (2002, 2022, 2042 and 2062). Also, it is assumed that other input variables are same with those described in the section 7.2 and the works duration is one week. The range of differences between two values are 0~10 %. Hence, it is considered that the results from the developed computer code are reliable enough to compare indirect costs of different maintenance options.

2) In principle, whole life costs of maintenance plans should be calculated as a sum of direct costs and traffic delay costs. However, the two cost components have different characteristics, and it is unrealistic to add direct costs and traffic delay costs together. Therefore, it is considered to be desirable to assign weighting factors to direct cost and traffic delay cost (or indirect cost here), so that total costs from different combinations can be easily calculated. The examples of cost combinations are:

- Direct cost only
- Indirect cost only
- Total cost (= Direct cost + Indirect cost)
- Arbitrary cost (=Direct cost (partly) + indirect cost (partly)).

By exploring these alternatives, the bridge manager can explore the implications of different preferences and prepare a range of plans that will suit specific overall objectives and societal targets.

Chapter 5

Life Cycle Assessment

5.1 Introduction

In order to accomplish the goal of sustainable bridge management, environmental impact from bridge maintenance activities should be minimised. This environmental impact may come from various sources, including the production and transportation of materials, operation of machinery at works site, and additional fuel consumption of vehicles due to traffic disruption.

Life Cycle Assessment (LCA), a scientific tool to quantify and evaluate the environmental impact of product system, can be used to select environmentally friendly construction options on a quantitative basis. In practice, LCA methodology has often been used to identify design and/or management options in buildings and bridge structures with the primary aim of reducing environmental impacts. However, the application of LCA to bridge management has, so far, been quite limited.

This study will use LCA methodology in order to quantify and evaluate the environmental impact related to bridge maintenance activities. For this purpose, the following items will be described sequentially:

(1) the phases of LCA and their characteristics;
(2) A comparison of published Life Cycle Impact Assessment methodologies;
(3) A review of previous research on the application of LCA to building and bridge structures;

(4) Uncertainty sources associated with LCA, and their modelling;

(5) Direction and limitation in applying LCA to bridge management;

(6) Environmental data for bridge management.

5.2 Phases of Life cycle assessment

Development in LCA methodology has been led mainly by SETAC (the Society of Environmental Toxicology and Chemistry), ISO (the International Organisation for Standardization), and UNEP (the United Nations Environmental Programme). Based on their efforts, many generic methodologies and a number of applications have been produced all over the world. In this study, the characteristics of LCA shall be reviewed mainly based on ISO standards 14040 series (Environmental management – Life Cycle Assessment) and documents published by SETAC.

In ISO 14040 [146], Life Cycle Assessment is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle." As shown in Figure 5.1, the phases of LCA include definition of goal and scope, inventory analysis, impact assessment and interpretation of results. A successful LCA project can be accomplished by the interaction of these four phases. Their details are given below.

5.2.1 Goal and scope definition

The goal and scope definition is the phase in which the initial choices to determine the working plan of the entire LCA project are made. The definition of goal of the LCA study includes stating the intended application, the reasons for carrying out the study and the intended audience. On the other hand, the scope definition step establishes the main characteristics of an intended LCA study. According to ISO 14040 [146], the main items considered in the scope definition phase include:

- The functions of the product system(s);
- The functional unit;

- The product system to be studied, and its boundary;
- Allocation procedures;
- Types of impact and methodology of impact assessment, and subsequent interpretation to be used;
- Data requirements.

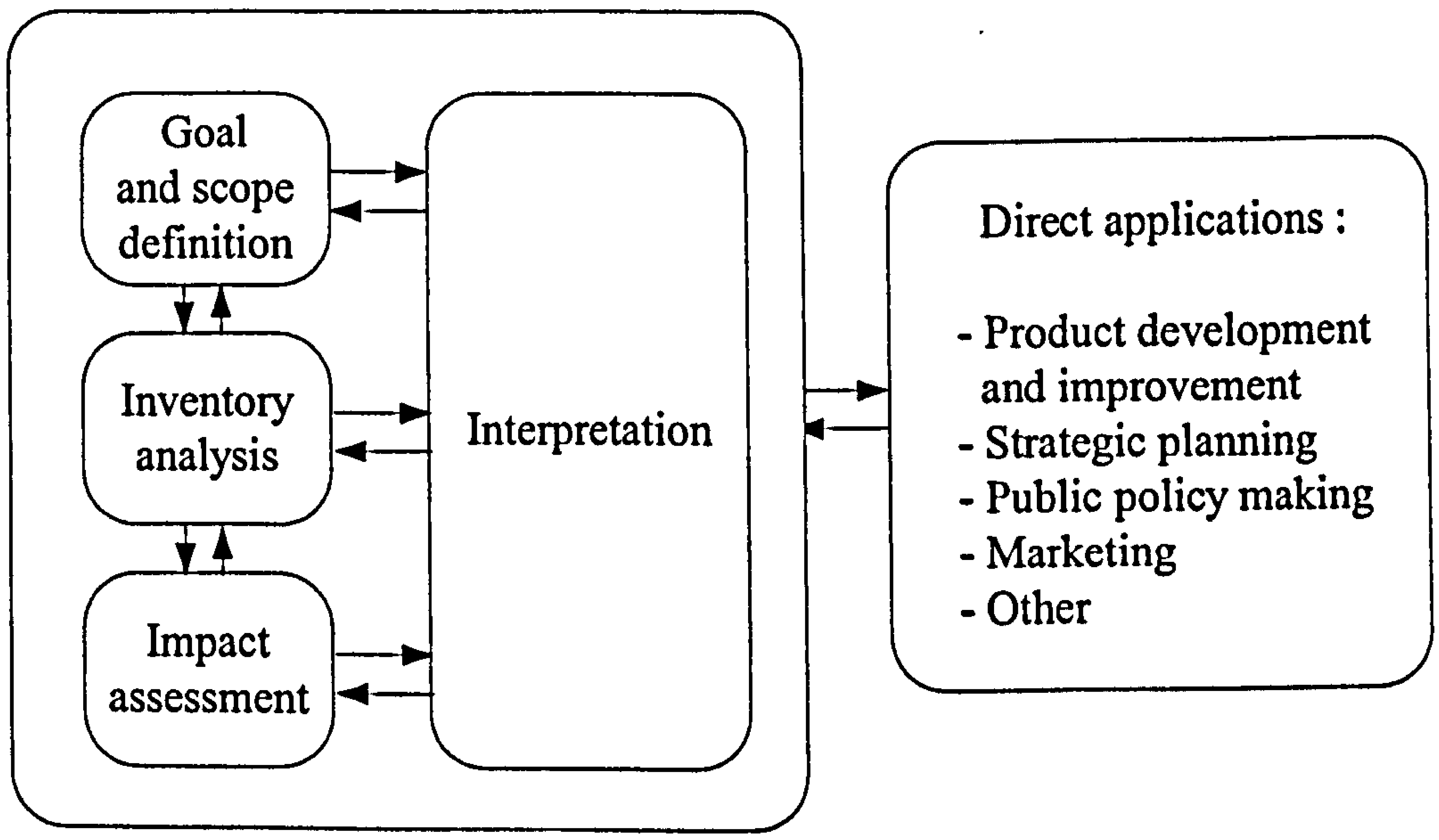


Figure 5.1 Phases of an LCA [140]

5.2.2 Inventory analysis

Life Cycle Inventory analysis (LCI) involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. According to Guinee et al. [147], the specific activities in LCI phase include:

- Setting the system boundaries (between economy and environment, with other product systems, and in relation to cut-off);
- Designing the flow diagrams with unit processes;
- Collecting the data for each of these processes;
- Performing allocation steps for multifunctional processes;
- Completing the final calculations.

Its main result is to produce an inventory table listing the quantified inputs from and outputs to the environment associated with the functional unit. Interpretations may be drawn from these data, depending on the goals and scope of the LCA. These data also constitute the input to the life cycle impact assessment [146].

5.2.3 Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) is the phase in which the set of results of the inventory analysis is further processed and interpreted in terms of environmental impacts and societal preferences [147]. Basic guidance on the LCIA phase can be found in ISO 14042 [148].

The general framework of the LCIA phase is composed of several mandatory elements that convert LCI results to indicator results. In addition, there are optional elements for normalisation, grouping or weighting of the indicator results and data quality analysis techniques. The elements of the LCIA phase are illustrated in Figure 5.2, and their detailed characteristics are further discussed in the following paragraphs.

<u>Selection of impact categories, category indicators</u>

The first step in LCIA phase is to select a set of impact categories. These impact categories are selected by LCA practitioners based on the goal of their particular study. There are two basic approaches to select impact categories. They are the mid-point approach (or problem-oriented approach) and the end-point approach (or damage-based approach). The mid-point approach links LCI results to environmental problems such as climate change, ozone depletion or acidification, etc. The category indicators calculated in the mid-point approach can represent the magnitude of environmental concern, but cannot explain the subsequent damages to humans, animals and plants. On the other hand, the end-point approach tries to connect LCI results up to the damage to human health, ecosystem and resources. Generally, damage indicators are calculated by assigning the mid-point indicators to one or more damage categories.

The end-point approach is much easier to understand and interpret, but it is not straightforward to connect each type of LCI result with a relevant damage contribution mainly due to the limits of current scientific knowledge. On the other hand, a mid-point approach has lower uncertainty associated with its modelling, but the interpretation of results is more difficult because a large number of impact category indicators should be evaluated simultaneously.

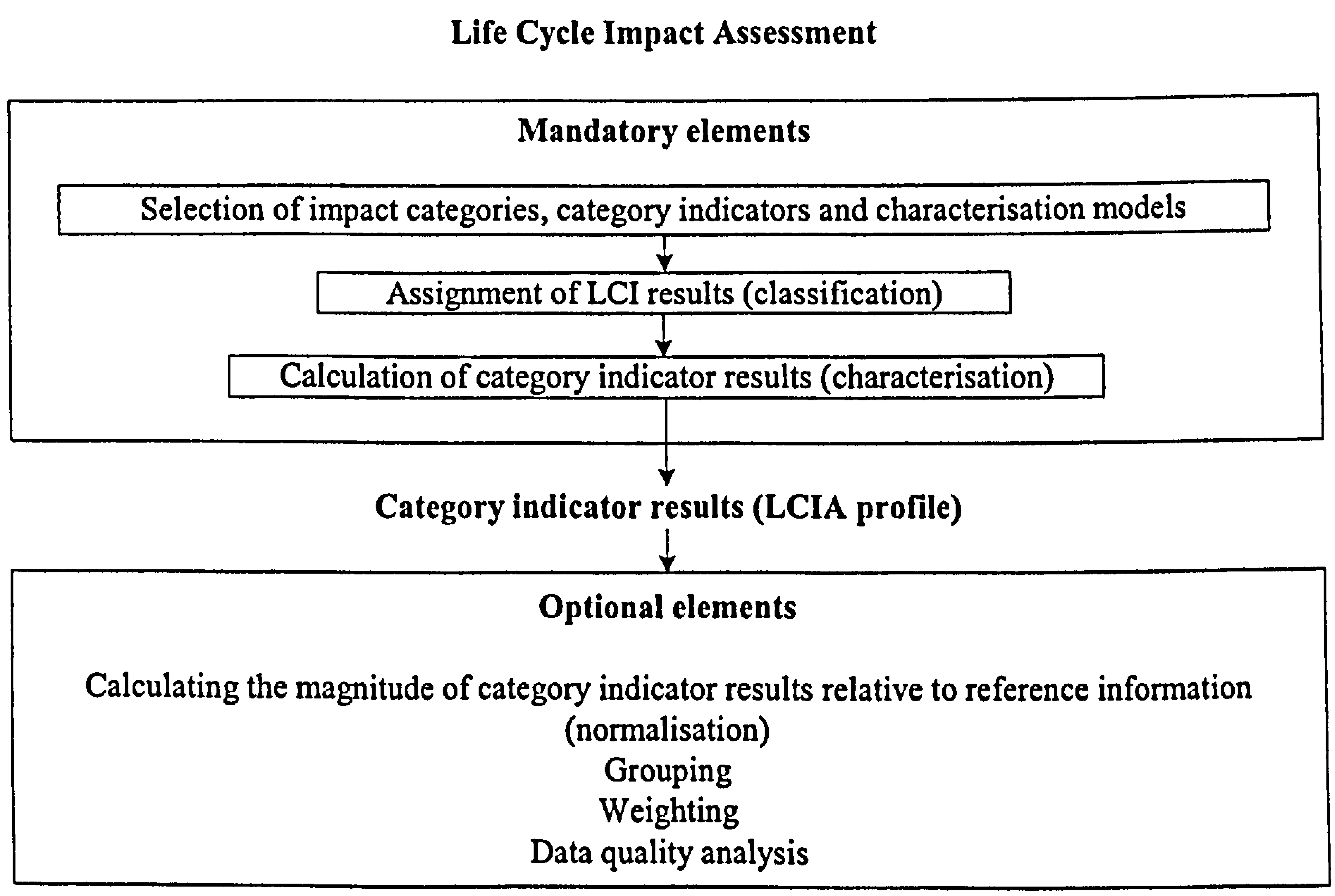


Figure 5.2 Elements of the LCIA phase ([148])

Tables 5.1 and 5.2 illustrate the impact categories normally used in the mid-point approach and end-point approach, respectively. Their details can be found in several references [147, 149, 150]. The selection of the approach and relevant impact categories depends on the goal and scope of LCA study and user's preference.

Classification

In this step the LCI results are assigned on a purely qualitative basis to the various pre-selected impact categories.

Table 5.1 Impact categories of mid-point approach, their category indicator and unit (Adapted from [147])

Impact categories	**Sub categories (if any)**	**Category indicator**	**Unit of indicator result**
Depletion of abiotic resources		Depletion of the ultimate reserve in relation to annual use	kg (antimony eq.)
Depletion of biotic resources			
Impacts of land use	Land competition Loss of life support function Loss of biodiversity	Land occupation	$m^2 \cdot yr$ (land use)
Climate change		Infrared radiative forcing (W/m^2)	kg (CO_2 eq)
Stratospheric ozone depletion		Stratospheric ozone breakdown	kg (CFC-11 eq)
Human toxicity		Acceptable daily intake/predicted daily intake	kg (1,4-dichlorobenzene eq)
Ecotoxicity	Freshwater aquatic ecotoxicity Marine aquatic ecotoxicity Terrestrial ecotoxicity Freshwater sediment ecotoxicity Marine sediment ecotoxicity	Predicted environmental concentration / predicted no-effect concentration	kg (1,4-dichlorobenzene eq)
Photo-oxidant formation		Tropospheric ozone formation	kg (ethylene eq)
Acidification		Deposition/acidification critical load	kg (SO_2 eq)
Eutrophication		Deposition / N/P equivalent in biomass	kg (PO_4 eq)
Impacts of ionizing radiation		Disability-adjusted life years (DALY)	yr
Odour	Malodourous air Malodourous water	Volume of air filled to the odour threshold value	m^3 (air)
Noise		Sound	$Pa^2 \cdot s$ (sound)
Casualties		Number of victims	Dimensionless

* Characterisation model used in each impact category can be found in [147].

Table 5.2 Impact categories of end-point approach, indicator unit and relevant mid-point impact categories (Adapted from [149, 150])

Impact categories (*)	**Indicator unit**	**Relevant mid-point impact categories**
Damage to human health	DALY (Disability Adjusted Life Years) or HALE (Healthy Years Life Expectancy)	Climate change Stratospheric ozone depletion Human toxicity Photo-oxidant formation Impacts of ionizing radiation Odour Noise Casualties
Damage to ecosystem	PDF (Potentially Disappeared Fraction of species) or PAF (Potentially Affected Fraction of species)	Depletion of biotic resources Impacts of land use Ecotoxicity Acidification Eutrophication
Damage to resources	MJ Surplus energy	Depletion of abiotic resources

* More detailed damage categories can be found in [149].

Characterisation

In the characterisation step the LCI results assigned qualitatively to a particular impact category in classification are quantified in terms of a common unit for that category, allowing aggregation into a single score: the indicator result. The collection of indicator results, referred to as the LCIA profile, provides information on the environmental issues associated with the inputs and outputs of the product system.

Normalisation

According to ISO 14042 [148], normalisation is an optional element which calculates the magnitude of indicator results relative to reference information. This is normally done by dividing indicator results by selected reference values. The reference information may relate to a given community (for example, global, regional, national or local), person or other system, over a given period of time. Through the normalisation step, it is possible to understand better the relative magnitude of each indicator result of the product system under study.

Grouping

Grouping is an optional step in which impact categories are assigned into one or more sets as predefined in the goal and scope definition. Grouping can be used to sort the impact categories on a nominal basis or to rank the impact categories in a given hierarchy based on value choices.

Weighting

Weighting is the process to convert indicator results or normalised results with selected weighting factors and possibly aggregate these weighted values across impact categories. The weighting step is not based on natural science but is based on value choices. There are three methods to determine weighting factors. They are as follows [150, 151]:

(1) The panel method: a panel of individuals assesses impact categories and proposes weighting factors;

(2) The distance to target method: the difference between current levels of environmental impacts and target levels is used to derive a weighting factor. When the difference is high, the weighting factor is high;

(3) The monetary method: an economic cost is placed on the environmental damage caused by an impact. The example of this method is Environmental Priority Strategies in Product Design (EPS) in which all damages are expressed in the same monetary unit: Environmental Load Units (ELU).

Weighting is the most controversial and difficult step in LCIA. Therefore, it may be desirable to use several different weighting factors and weighting methods to assess the consequences on the LCIA results of different value choices.

Table 5.3 summarises the characteristics of six LCIA methodologies published in European countries, namely:

(1) Eco-indicator 95 [152] and (2) Eco-indicator 99 [153] from PRé Consultants, the Netherlands;

(3) CML [147] from Leiden University, the Netherlands;

(4) Ecopoints [154] from BUWAL, Switzerland;

(5) EPS [155] from Chalmers University of Technology, Sweden;

(6) EDIP [156] from Danish EPA, Denmark.

Furthermore, Table 5.4 shows the normalisation and weighting factors used in three mid-point approach LCIA methodologies. Likewise, Table 5.5 and Table 5.6 display the normalisation and/or weighting factors of Eco-indicator 99 and EPS methodologies, respectively.

From these tables, it is certain that different LCIA methodologies can be used in different countries and situations, and it is important to select an appropriate LCIA methodology for a given LCA study. It may be possible to apply some of above methodologies to this study.

Table 5.3 The characteristics of published LCIA methodologies ([147, 151-156])

LCIA	Classification	Characterisation	Normalisation	Weighting
Eco-indicator 95	Netherlands and global perspective (Mid-point approach)	Fate and relative environmental intervention modelling	Divided by reference values which one European person causes in one year (Based on 1990 levels for Europe excluding former USSR)	Distance to target method (with additional subjective weighting to represent significance on human health and ecosystem impairment from a Netherlands perspective)
Eco-indicator 99	Netherlands and global perspective (End-point approach)	Actual damage modelling	Divided by damage caused by 1 European per year (mostly based on 1993 as base year)	Panel method - Individualist perspective - Egalitarian perspective - Hierarchist perspective
CML	Europe and global perspective (Mid-point approach)	Fate and relative environmental intervention modelling	Three reference situations - world in 1990, 1995 - West Europe in 1995 - the Netherlands in 1997	No weighting procedure included or recommended
Ecopoints	The Ecopoint system does not use a classification. It assesses impacts individually.	Characterisation modelling is not used.	Target value or critical emission for each impact category for Switzerland over one year. They are derived from Swiss policy.	Distance to target method (Calculated as the ratio of actual inventory value to the target/critical value for each impact category)
EPS	Swedish and global perspective (End-point approach)	Actual damage modelling	No formal normalisation introduced into method	Monetary method (Calculated as the willingness to pay (WTP) to restore impacts)
EDIP	Danish and global perspective (Mid-point approach)	Fate and relative environmental intervention modelling	Based on person equivalents for 1990	Distance to target method (The weighting factors are set to the politically set target emissions per person in the year 2000.)

Table 5.4 Comparison of normalisation and/or weighting factors of three mid-point approach LCIA methodologies (*)

	Eco-indicator 95			CML				EDIP		
	Sub-category	N.F	W.F	Sub-category	N.F			Sub-category	N.F	W.F
					Netherlands	Europe	World			
Climate change		7.65E-5	2.5		3.99E-12	2.12E-13	2.16e-14		1.15E-7	1.3
Ozone depletion		1.08	100		1.02E-6	1.2E-8	8.76E-10		4.95E-3	23
Acidification		0.00888	10		1.49E-9	3.66E-11	3.20E-12		8.06E-6	1.3
Photochemical oxidant formation		0.0558	12.5		5.49E-9	1.21E-10	9.27E-12		5.00E-5	1.2
Eutrophication		0.0262	5		1.99E-9	8.02E-11	7.59E-12		3.36E-6	1.2
Human toxicity	Heavy metal Carcinogens Winter smog	18.4 92 0.0106	5 10 5		5.31E-12	1.32E-13	1.67E-14	Air Water Soil	1.09E-10 1.69E-5 3.23E-3	2.8 2.5 2.5
Ecotoxicity	Pesticides	1.04	25	Freshwater aquatic	1.33E-10	1.98E-12	4.83E-13	water chronic	2.13E-6	2.3
				Marine aquatic	2.35E-13	8.81E-15	1.32E-15	Water acute	2.08E-5	2.3
				Terrestrial	1.04E-9	2.12E-11	3.79E-12	Soil chronic	3.33E-5	2.3
Abiotic resource depletion	Energy	6.29E-6	0		5.85E-10	6.66E-11	6.32E-12		0	0
Waste		solid	0					Bulk Hazordous Radioactive Slag/ashes	7.41E-4 4.83E-2 2.86E1 2.86E-3	1.1 1.1 1.1 1.1

*These values are from SimaPro program.

Table 5.5 Normalisation and weighting factors of Eco-indicators 99 methodology (*)

Damage Category	Individualist perspective		Egalitarian perspective		Hierarchist perspective	
	Normalisation factor	Weighting factor Avg / Individualist	Normalisation factor	Weighting factor Avg / Egalitarian	Normalisation factor	Weighting factor Avg / Hierarchist
Human health	121	400 / 550	64.7	400 / 300	65.1	400 / 300
Ecosystems Quality	2.22E-4	400 / 250	1.95E-4	400 / 500	1.95E-4	400 / 400
Resources	6.77E-3	200 / 200	1.68E-4	200 / 200	1.19E-4	200 / 300

*These values are from SimaPro program.

Table 5.6 Weighting factors of EPS 2000 methodology (*)

Damage Category (Unit)	Corresponding Impact category (Unit)		Factor	Weighting factor
Human health (ELU/Person Year)**	Life Expectancy	(Person Year)	85,000	1
	Severe Morbidity	(Person Year)	100,000	
	Morbidity	(Person Year)	10,000	
	Severe Nuisance	(Person Year)	10,000	
	Nuisance	(Person Year)	100	
Ecosystem Production Capacity (ELU/kg or H+)	Crop Growth Capacity	(kg)	0.15	1
	Wood Growth Capacity	(kg)	0.04	
	Fish and Meat Production	(kg)	1	
	Soil Acidification	(H+ eq.)	0.01	
	Production Capacity of Irrigation Water	(kg)	0.003	
	Production Capacity of Drinking water	(kg)	0.03	
Abiotic Stock Resource (-)	Depletion of resources	(ELU/kg)	1	1
Biodiversity (ELU)	Species Extinction	(-)	1.1E11	1

*These values are from SimaPro program. ** ELU: Environmental Load Unit

5.2.4 Interpretation

According to ISO 14043 [157], life cycle interpretation is a systematic procedure to identify significant issues; evaluate information from the results of the LCI and/or LCIA of a product system by completeness, sensitivity and consistency check; and finally reach conclusions, provide recommendation, and report the results in a transparent manner.

5.3 Application of LCA to construction industry

5.3.1 Application of LCA to building structure

The effect of the construction industry on environmental impact is tremendous, so there have been some efforts to apply LCA techniques to construction industry products and processes in order to identify environmentally preferable construction options.

In particular, LCA studies for buildings have been well developed, and many countries have their own LCA methodologies and/or tools for the environmental evaluation of building structures [158, 159].

First, there are some scoring methods that indicate the relative environmental performance on the basis of a number of building characteristics [159]. These include:

- Building Research Establishment Environmental Assessment Method (BREEAM) developed in the United Kingdom;
- EcoProfile for buildings, developed in Norway;
- Building Environmental Performance Assessment Criteria method (BEPAC) developed in Canada; and
- Leadership in Energy and Environmental Design (LEED) developed in the USA.

All these essentially consist of lists of suggestions aimed at improved environmental performance of buildings, linked to a score. Summing up these scores gives an overall score for the building. The scoring methods may emphasize different aspects of environmental performance.

Secondly, there are a number of LCA-based tools for buildings and construction such as those given below [39, 159]:

- "ECOPT-ECOPRO-ECOREAL", developed in Germany;
- IVAM, "ECO-QUANTUM", developed in the Netherlands;
- ATHENA Sustainable Materials Institute, "ATHENA™", developed in Canada;
- SBI, "BEAT", developed in Denmark;
- BRE, "ENVEST" developed in the United Kingdom; and
- EPA, "BEES", developed in USA.

These tools are designed for use at different levels. Therefore, they are based on different assumptions, data and methodologies. Especially, the "BEES" program of US EPA [160] and "Envest II" program of UK BRE both have brought economic and environmental data together, so it is possible to select preferable building option based on integration of economic and environmental performance score.

For this study it is appropriate to review the BRE methodology in more detail because it is based on UK specific environmental data for the construction industry and the values used in LCIA reflect concerns and value choices of the UK society.

Table 5.7 presents an overview of the BRE Environmental profiles database. In order to collect these data, BRE obtained detailed process information from manufacturers of UK building materials, products and components; it utilized nationally collected statistical data on transport, energy and greenhouse gas emissions; and in cases where there were no available primary data, data were extracted from existing commercial databases such as SimaPro, IVAM LCA Data 2.0, and SBI Database.

The inventory data for the BRE methodology are of a 'per tonne data' or a 'per square metre' type. The materials are presented as "cradle to gate" profiles on a "per tonne" basis. Installed elements are presented on a "cradle to site" basis and are calculated "per square metre" of element. Sixty year life elements are presented as a "cradle to grave" profile, taking account of their maintenance, replacement and disposal rates for a sixty year life. These have also been calculated on a "per square metre" basis.

Table 5.7 BRE Environmental Profiles database (Adapted from [40])

No	Accessibility	Data type
D1	Restricted Access Database	Materials and Components Inventory Data
D2	Restricted Access Database	Materials Characterised and Normalised Data
D3	Public Access Database	Materials and Components Inventory Data
D4	Public Access Database	Materials Characterised and Normalised Data
D5	Public Access Database	Installed Building Elements Inventory Data
D6	Public Access Database	Installed Building Elements Characterized and Normalised Data
D7	Public Access Database	60 year life Building Elements Inventory Data
D8	Public Access Database	60 year life Building Elements Characterised Data

Table 5.8 shows the impact categories, category indicators, normalisation and weighting factors of BRE's UK Ecopoints methodology. The weighting factors were derived from a consultation process with several expert groups (Panel method). The Ecopoint score for 1 unit of category indicator shown in the last column of Table 5.8 is calculated by dividing the weighting factor by the corresponding normalisation factor of each impact category. These values provide the necessary factors so that the impact from any product/process can be evaluated in terms of UK Ecopoints. Thus, a single environmental score, i.e. in UK Ecopoints, which represents the total environmental impacts, can be calculated by summing up the environmental impact of each category using the formula below:

$$\text{UK Ecopoints} = \sum \text{Amount of category indicator} \times \text{Ecopoint score for 1 unit} \quad (5.1)$$

Table 5.8 LCIA characteristics of BRE's UK Ecopoints methodology ([41])

Impact categories	Category indicator	Normalisation factor (UK impacts per citizen)	Weighting (%)	Ecopoint score for 1 unit
Climate change	kg CO_2 eq	12,269	35	0.0029
Acid deposition	kg SO_2 eq	58.9	5	0.0849
Ozone depletion	kg CFC_{11} eq	0.3	8	26.27
Pollution to air:				
human toxicity	kg tox	90.7	6.5	0.077
Low level ozone creation	kg ethane eq	32.2	3.5	0.12
Fossil fuel depletion and extraction	toe	4.09	11	2.69
Pollution to water:				
human toxicity	kg tox	0.01	2	200
ecotoxicity	m^3 tox	177,948	4	0.00002
eutrophication	kg PO_4 eq	8.0	4	0.50
Minerals extraction	tones	5.0	3	0.60
Water extraction	litres	417,583	5	0.00001
Waste disposal	tones	7.2	6	0.83
Transport pollution and congestion: freight	tonne km	4141	7	0.0017
		Sum	100	

In this methodology, the total number of Ecopoints for all the impacts that arise per UK citizen in one year amounts to 100.

5.3.2 Application of LCA to bridge structure

Compared with those for buildings, the number of LCA study cases for bridge construction or maintenance is very limited [52, 161-165], and the methodologies used are neither consistent nor systematic. This is due to the complex nature of LCA, and a lack of credible data for bridge structures and their maintenance options [166]. The characteristics of LCA case studies for bridge structures are contrasted in Table 5.9 whereas some of the main conclusions are summarised below.

Steele [162, 163] presents the most developed form of LCA examples for bridge structures, in particular focusing on the environmental impacts of brick arch bridges. For life cycle impact assessment, he used Eco-indicator 95 and Eco-indicator 99 methodologies. His main conclusions were:

- In general, bridge construction represents the single biggest contributor to environmental impact over the entire bridge life cycle. However, the environmental impact from structure closure and traffic diverting can, on occasion (if the disruption period is long), be a source of greater environmental impact;

- It is the manufacture of the material components of a structure that is the source of greatest environmental impact. In contrast to the. manufacture of materials, transportation of materials and site processes associated with construction, maintenance and strengthening all represent only a minor burden;

- Basic brickwork maintenance has only minimal impact on environment. These activities, including repointing and brickwork renewal, provide 'good value' and represent long-term environmental savings.

Itoh [52, 161] focused only on CO_2 emission as an indicator of environmental impacts and calculated both construction cost and construction plus maintenance cost for bridges. Even though CO_2 emission is an important contributor to global warming, it does not account for total environmental impact. The main conclusions were:

- From a comparison between three bridge types, he concluded that the simple steel non-composite box girder bridge has the highest environmental impact value. In comparison, the simple pre-tensioned concrete T-girder bridge and the simple prestressed concrete box girder bridge has lower impacts. This is due to the use of a larger amount of steel in the former case which has a higher unit impact value;

- The energy consumption from construction equipment is in the order of 5% in these bridge types. The total CO_2 emissions from construction equipment are in the order of less than 5%. This shows that the major portion of environmental impact of these bridges is due to the manufacture of construction materials themselves;

- The minimised girder bridge (MGB) which is a relatively new type of bridge developed by the Japan Highway Public Corporation, compared with conventional bridge (CB) (see Figure 5.3), can reduce CO_2 emission and life cycle cost. Itoh also found that prolonging the service life of a bridge component is invaluable for both bridge types from the viewpoints of the life cycle CO_2 emission and the life cycle cost.

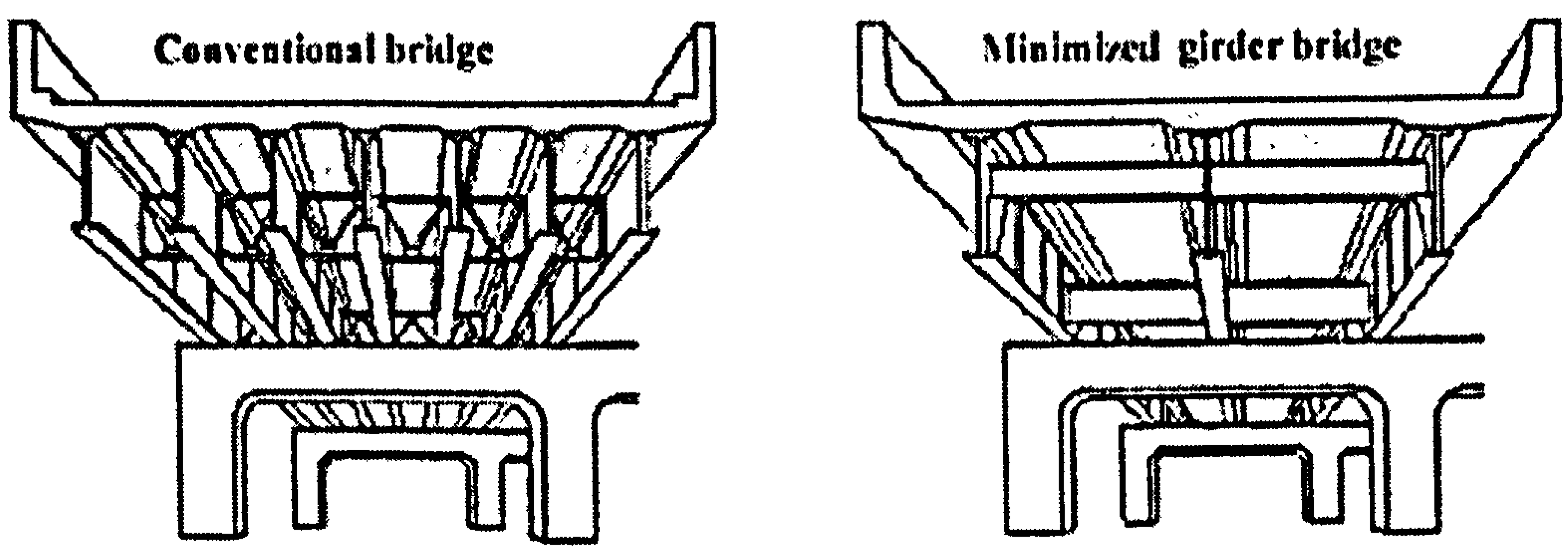


Figure 5.3 Conceptual graphs of CB and MGB ([52])

Widman [164] analysed the environmental impacts of Swedish steel bridges. As a life cycle impact assessment method, he used the EPS method, Environmental Theme Method and Ecoscarcity Method, but these methods are not used often in other countries. The main conclusions were:

- Vehicles carrying the materials and products contribute an important part of the CO and NO_x emissions. The main sources of the CO_2 emissions are manufacturing of cement and steel;

- The emissions CO_2, NOx, SO_2 and CO correspond to more than 95% in weight out of the total airborne emissions. A reduction in these emissions will therefore improve the total environmental impact from building and using the bridge;

- Optimisation of the material amounts used for construction of the bridge also reduces the total environmental burden. As the environmental effects from the maintenance part are very small, it is not important to increase the longevity by using a lot of corrosion protective substances or extra amounts of material to prevent material deterioration.

Horvath [165] compared the environmental impacts of a steel plate girder bridge to those of a post-tensioned bulb-tee girder bridge. He used economic input-output based life cycle assessment (EIO-LCA) to calculate the total inputs, hence the environmental impacts of the materials extraction, the materials processing and the manufacturing stages. Three major groups of environmental impacts are quantified: (1) TRI (US EPA's Toxics Release Inventory) chemical emissions; (2) hazardous waste generation; and (3) conventional air pollution emissions. For use phase environmental impacts, only the painting of the steel structure was considered and the environmental impacts of painting were compared with those of the girder production. The main conclusions were:

- When only the initial construction is considered, concrete girders appear to have lower overall environmental impacts than steel girders;

- All resource requirement and environmental outputs of painting are much less than those of girder production. However, conventional air pollutants such as SO_2, NO_x, methane and VOC emissions are significantly higher for the paint manufacturing than for the production of all girders;

- The reuse or recycle of steel may save input resources and environmental pollution of steel bridges, but concrete cannot easily be reused.

Table 5.9 The comparison of LCA examples for bridge structures

Category	Steele ([162, 163])	Itoh ([161])	Itoh ([52])	Widman ([164])	Horvath([165])
Purpose	To evaluate the environmental impact of brick arch bridge management	To compare the environmental impacts of the several bridge types	To compare the environmental impacts between CB and MGB.	To show the application of LCA to steel bridges	To compare concrete and steel bridges in terms of environmental impacts.
Bridge type considered	Brick arch bridge	- Pre-tensioned T-girder bridge - PC box girder bridge - Steel non-composite box girder bridge	- Conventional bridge (CB) - Minimised girder bridge (MGB)	- Steel box girder bridge - Steel I-girder bridge	- Steel plate girder bridge - Post-tensioned bulb-tee girder bridge
Life cycle considered	- construction - maintenance - strengthening (saddle vs. anchor)	- construction	- construction - maintenance - replacement	- construction - maintenance - demolition	- construction - maintenance (painting only)
Traffic disruption at maintenance stage	Based on simplified assumption	X	X	X	X
LCI data source	BRE SimaPro	Data from Japan	Data from Japan	Data from Sweden, Norway and Finland	EPA's Toxics Release Inventory
Inventory analysis	Intermediate step	- CO_2 emission - Energy	- CO_2 emission	- CO_2 -SO_2 - NO_x - Energy	- H_2SO_4 -SO_2 - NO_x -Methane - VOC
Impact Assessment	- Eco-indicator 95 for (1) - Eco-indicator 99 for (2)	X	X	- EPS method - Environmental Theme Method - Ecoscarcity Method	X
Economic Analysis	X	Yes (Construction cost only)	Yes (Construction and maintenance cost)	No	Yes (Construction cost only)
Integration of LCA and LCC	X	X	X	X	X
Uncertainty analysis	X	X	X	X	X

5.4 The uncertainty in LCA

Uncertainty in LCA can be introduced during three stages [167]:

(a) Input data: physical, modelling or statistical uncertainty in input data.

(b) LCA calculation: uncertainty propagation in calculation.

(c) Output data: uncertainty in interpretation and decision-making.

More precisely, Huijbregts [69] categorised the uncertainty (including variability) in LCA into six types namely: (1) parameter uncertainty; (2) model uncertainty; (3) uncertainty due to choices; (4) spatial variability; (5) temporal variability; and (6) variability between object/sources. Björjlund [168] divided the parameter uncertainty into data inaccuracy, data gaps and unrepresentative data, and added epistemological uncertainty, mistakes and estimation of uncertainty as additional sources of uncertainty. In table 5.10, examples of uncertainty related to the phases of LCA are shown.

The types and sources of uncertainty and variability in LCA are so complex that different tools have been suggested to reduce or illustrate the problems [69, 70, 168-177]. Table 5.11 gives an overview of available tools for treatment of uncertainty in LCA.

The initial research treating uncertainty problem in LCA focused on the input data quality [172, 173, 175, 176, 178, 179]. The two main solutions proposed for data quality problems are data quality indicator (DQI) and use of stochastic models [176]. Data quality can be expressed through information about the data (DQI) concerning uncertainty, reliability, completeness, age, geographical area, process technology or technological level [168]. For example, the SimaPro program uses DQI requirements such as time period, geography, technology, representativeness, allocation and system boundaries [150]. In order to introduce the stochastic model, Kennedy et al. [175] used the DQI values to decide the probability distribution parameters of input data.

Table 5.10 Point of introduction in the LCA of different types of uncertainty, and examples of possible sources (from [168])

Type	LCA phase				
	Goal and scope	**Inventory**	**Choice of impact categories**	**Classification**	**Characterisation**
Data inaccuracy		Inaccurate emission measurements			Uncertainty in life times of substances and relative contribution to impacts
Data gaps		Lack of inventory data			Lack of impact data
Unrepresentative Data		Lack of representative inventory data			
Model uncertainty		Static instead of dynamic modelling. Linear instead of non-linear modelling			Static instead of dynamic modelling. Linear instead of non-linear modelling
Uncertainty due to choices	Choice of functional unit, system boundaries	Choice of allocation methods, technology level, marginal/average data	Leaving out known impact categories		Choice of characterisation methods
Spatial variability		Regional differences in emission inventories			Regional differences in environmental sensitivity
Temporal variability		Differences in yearly emission inventories			Choice of time horizon. Changes in environmental characteristics over time
Variability between objects/sources		Differences in performance between equivalent processes			Differences in environmental and human characteristics
Epistemological uncertainty	Ignorance about relevant aspects of studied system	Ignorance about modelled processes	Impact categories are not known	Contribution to impact category is not known	Characterisation factors are not known
Mistakes	Any	Any	Any	Any	Any
Estimation of uncertainty		Estimation of uncertainty of inventory parameters			Estimation of uncertainty of characterisation parameters

Table 5.11 Overview of tools available to address different types of uncertainty in LCA (Adapted from [168])

		Data inaccuracy	Data gaps	Unrepresentative data	Model uncertainty	Uncertainty due to choices	Spatial variability	Temporal variability	Variability in objects/sources	Epistemological uncertainty	Mistakes	Estimation of uncertainty
Data Quality	Standardisation					x					x	
	Data bases		x	x								x
	Data quality goals	x		x								
	Data quality indicators	x		x								
	Validation of data										x	
	Parameter estimation		x									
	Additional measurements	x	x	x					x			
	Higher resolution models				x		x	x				
	Critical review		x	x		x				x	x	x
Sensitivity analysis	Sensitivity analysis	x		x	x	x	x	x	x			
	Uncertainty importance analysis	x		x	x	x	x	x	x			
Uncertainty analysis	Classical statistical analysis	x					x	x	x			
	Bayesian statistical analysis	x					x	x	x			
	Interval arithmetic	x										
	Vague error intervals	x										
	Probabilistic simulation	x							x			
	Scenario modelling			x	x	x	x	x	x			
	Rules of thumb	x										

Sensitivity analysis or uncertainty importance analysis can be used to find the significant input parameters. These methods estimate the effects on the outcome of a study of the chosen data. Sensitivity analysis uses arbitrarily selected ranges of variation, while uncertainty importance analysis is based on known or estimated ranges of uncertainty [168]. Figure 5.4 illustrate how to find the key issues from the uncertainty importance analysis. However, the problem of sensitivity analysis is that the superposition of effects is seldom considered [169]. With the number of uncertain parameters entering into the LCA process it could be necessary to consider some combined effects.

On the other hand, uncertainty analysis is a systematic procedure to ascertain and quantify the uncertainty introduced into the results due to the cumulative effects of input uncertainty and data variability. Uncertainty analysis can be performed by estimating the uncertainty of each parameter, expressing it as uncertainty distributions, and propagating the uncertainty through models to the final output [168]. Among the techniques for the uncertainty analysis shown in table 5.11, probabilistic simulation, and in particular Monte Carlo simulation, is the preferred analysis tool due to ease of application and readily understood basis. Several case studies [167, 169, 177] showed the applicability of Monte Carlo simulation to LCA studies, but these studies treated only life cycle inventory analysis.

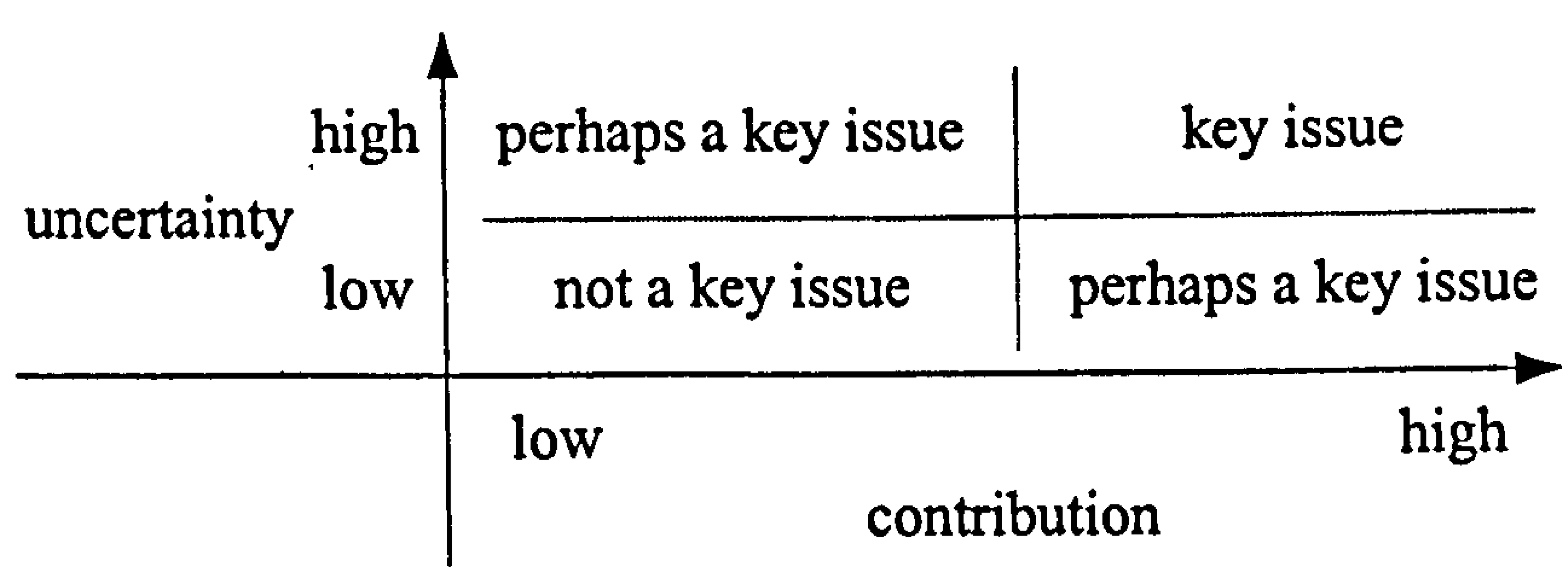


Figure 5.4 Finding key issues in an uncertainty importance analysis. ([178])

At present, it seems that the need for uncertainty analysis in LCA studies is acknowledged widely but the applications are limited. Ross et al. [68] showed that 47% of the 30 reviewed reports and articles about LCA studies acknowledged the uncertainty of the result, but only three included some sort of quantitative or qualitative uncertainty analysis. One of the reasons for this result is that the majority of LCA-software programs cannot deal with uncertainty estimates of input parameters, partly because this information was not available up to now. Another reason is that the absence of computational tools for handling such information has lowered the priority for the collection of these data [180].

In this study, the Monte Carlo Simulation technique will be applied to model the uncertainty of LCA input data. However, a prerequisite for this approach is the collection of LCA data represented by probability distributions. Therefore, the applicability of the proposed methodology can vary according to usability of proper data, and it is considered that data collection should be done together with the development of the methodology.

5.5 The application of LCA to bridge management

5.5.1 Introduction

The application of LCA to bridge management aims at evaluating environmental impacts of alternative bridge maintenance options and finding maintenance plans or practices which minimise environmental impacts.

Environmental impacts associated with bridge maintenance activities can be produced from maintenance works themselves such as production of materials, delivery, machinery operation, electricity use and waste disposal as well as from the additional fuel consumption of vehicles when traffic disruption happens. For convenience, the former is classified as direct and the latter as indirect environmental impacts.

Accordingly, the total environmental impacts from one maintenance plan which is composed of several maintenance activities undertaken in different future times can be calculated by using the following expression.

$$E = (E_{1d} + E_{1i}) + (E_{2d} + E_{2i}) + \cdots + (E_{nd} + E_{ni}) \qquad (5.2)$$

Here, the numbers in subscript represent the order of future maintenance activities and subscript d and i represent direct and indirect impact, respectively.

However, the application of LCA to bridge management is not an easy task. The main obstacle in performing an LCA study for bridge management is the lack of environmental data. As Steele [166] already mentioned, the number of materials used within the construction industry is enormous, and the polluting effects of these materials are not well known. Furthermore, bridge management activities have huge variability, so the standardisation of the specification of maintenance works is a complex procedure. This study has also been limited by this situation. Clearly, environmental data collection for all potential bridge maintenance works is beyond this study's scope. Data collection will be limited to several representative maintenance options for concrete bridges but the developed methodology could equally be applied to other construction forms should the necessary data become available.

The basic assumptions introduced in applying LCA methodology in this study and the calculation of resulting environmental scores is explained below.

5.5.2 Basic assumptions

(1) Intended application

The main goal is to evaluate the environmental performance of four alternative maintenance options for RC slab structures using Ecoindicator 95 and 99, and use the calculated environmental scores as a basic database in order to find an optimal bridge maintenance plan in terms of sustainability. Considered maintenance options are concrete repair, waterproofing, cathodic protection and replacement of element.

(2) Functions of maintenance options

The four maintenance options under analysis are representative of the key preventative or essential maintenance options of a RC slab superstructure against chloride attack. Other options in Table 3.1 may be applied for the same purpose, but they are not frequently used in real situations or only used in a particular structure or time. Therefore, alternatives in this study are limited to the four maintenance commonly used options specified above.

(3) Functional unit

The functional unit is defined as "the materials and operations required to repair/reconstruct 1m^2 of RC slab structure". The repair thickness changes according to the practice/characteristics of the options, so any single repair thickness is not specified as a functional unit here. Likewise, this study aims to combine different options in order to develop maintenance plans and add their environmental scores, so any specific time period is not given as a functional unit. Instead, the time period for analysis and effective lives of maintenance options, etc. are provided in input file.

More specifically, direct impacts per 1m^2 are quantified based on material input, energy use and waste disposal, etc. On the other hand, indirect impacts are calculated for whole bridge structure and are then converted to values per 1m^2 by dividing them by the superstructure's area.

(4) Boundary of studied system

The scope of the assessment can be categorised as Cradle to gate, Cradle to site, and Cradle to grave according to the processes taken into account as shown below.

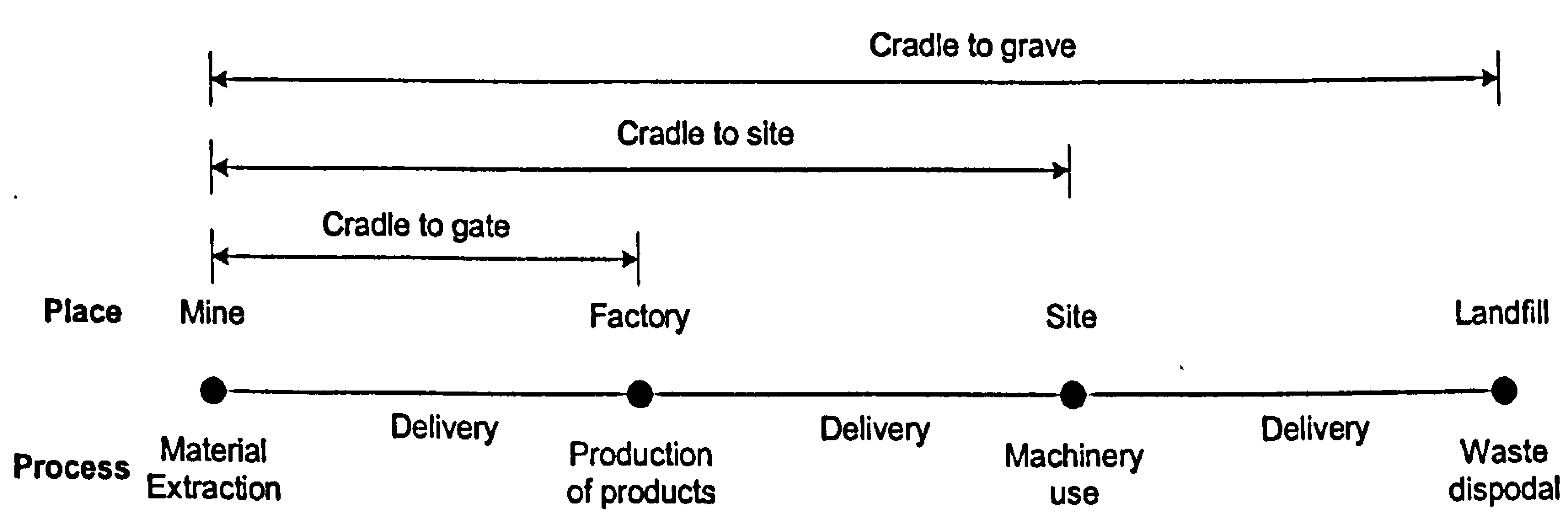


Figure 5.5 Scope of assessment and corresponding approaches

In this study, efforts are made to apply cradle to grave approach as much as possible. More specifically, processes corresponding to the cradle to gate approach as well as electricity use and waste disposal are considered. However, delivery to site and machinery use in site are not included mainly due to the high variability and lack of reliable data. However, it is generally acknowledged that transportation of materials and site processes represent only minor impacts in the life cycle [162, 163].

Therefore, it is considered that most of the environmental impacts from maintenance options can be covered by the present study's approach. The system diagrams for the four maintenance options considered herein are given in Appendix A.

(5) Source of environmental data

This study is based on secondary data sources from databases available in the SimaPro program [154]. Most of the environmental data in the SimaPro program reflect recent West European industry situations, so it is assumed that they can be directly applied to a UK situation. More specifically, most of the environmental data used in this study are extracted/combined from the 'IDEMAT 2001' database library which has been developed at Delft University of Technology, department of industrial design engineering, under the IDEMAT project. The 'IDEMAT 2001' database provides environmental data related to the production of materials used in many areas including the construction industry. Therefore, the detail LCI data used in this study can be found in SimaPro program [154] and full account of LCI data used in calculations are not described here.

(6) Selection of LCIA methodology

This study is akin to a 'Design for Environment (DfE)' problem [181, 182]. Therefore, it is preferable to represent the total environmental impacts as a single score so that the comparison of different alternatives can be straightforward. In other words, it is necessary to adopt an LCIA methodology which has normalisation and weighting phases.

BRE UK Ecopoints methodology which represents UK specific circumstance, or Eco-indicator 95 and Eco-indicator 99 methodologies which reflect West Europe situations could be selected as an LCIA methodology for a UK bridge management case study. On the other hand, the other LCIA methodologies given in Table 5.3 such as CML, Ecopoints, EPS and EDIP are more complex to interpret in the characterisation, normalisation or weighting stages; for this reason, they are not selected as an alternative LCIA methodology in this study.

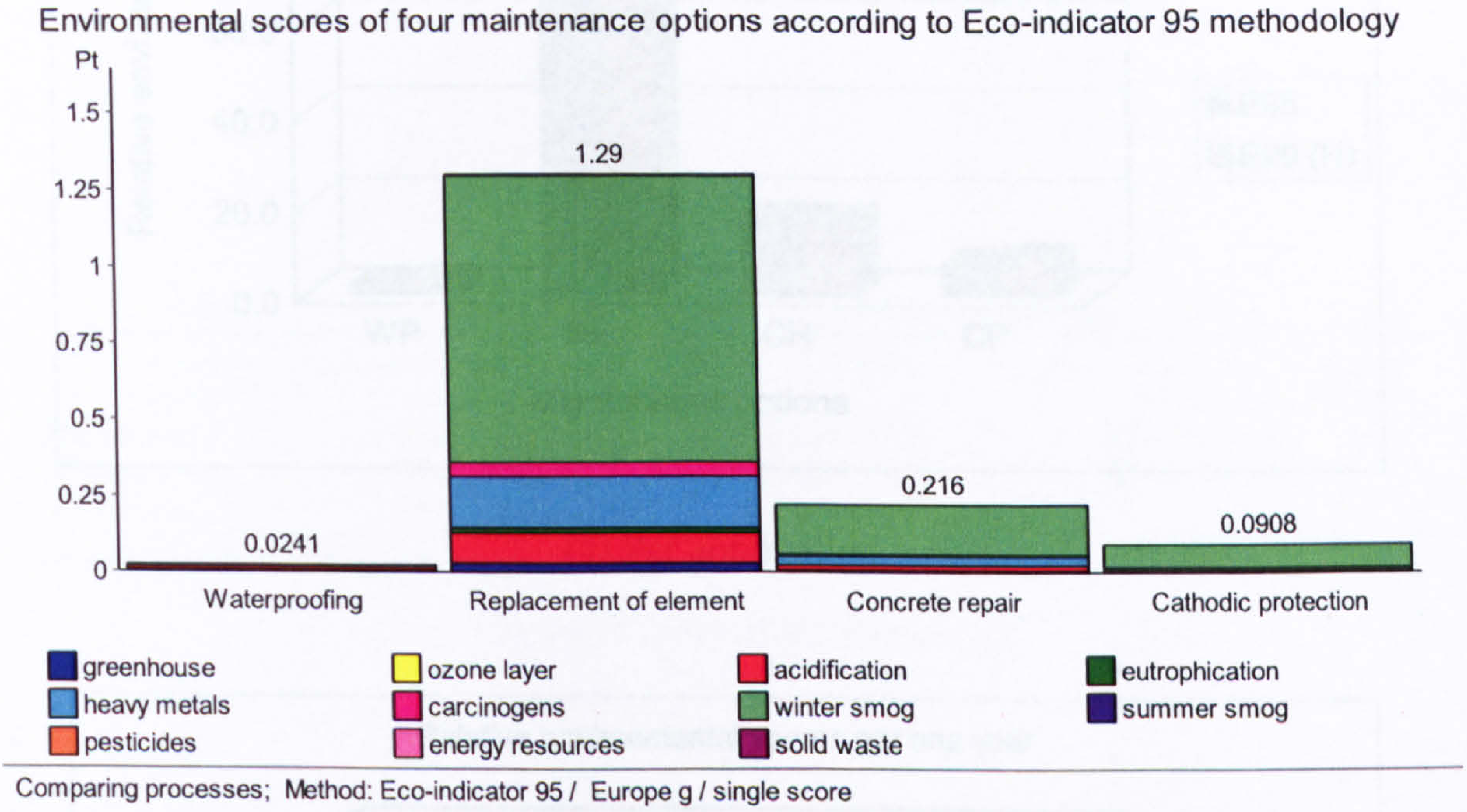
The selection of LCIA methodology depends on the accessibility to environmental data or methodology itself. BRE UK Ecopoints methodology and its databases have been developed mainly for building structures, and its accessibility is limited. On the other hand, Eco-indicator 95 and Eco-indicator 99 methodologies can be applied for more general applications including bridge maintenance activities if an appropriate database is available. Therefore, this study will use Eco-indicator 95 and Eco-indicator 99 methodologies as tools for calculating single environmental scores of maintenance options.

5.5.3 Calculation of direct environmental impacts

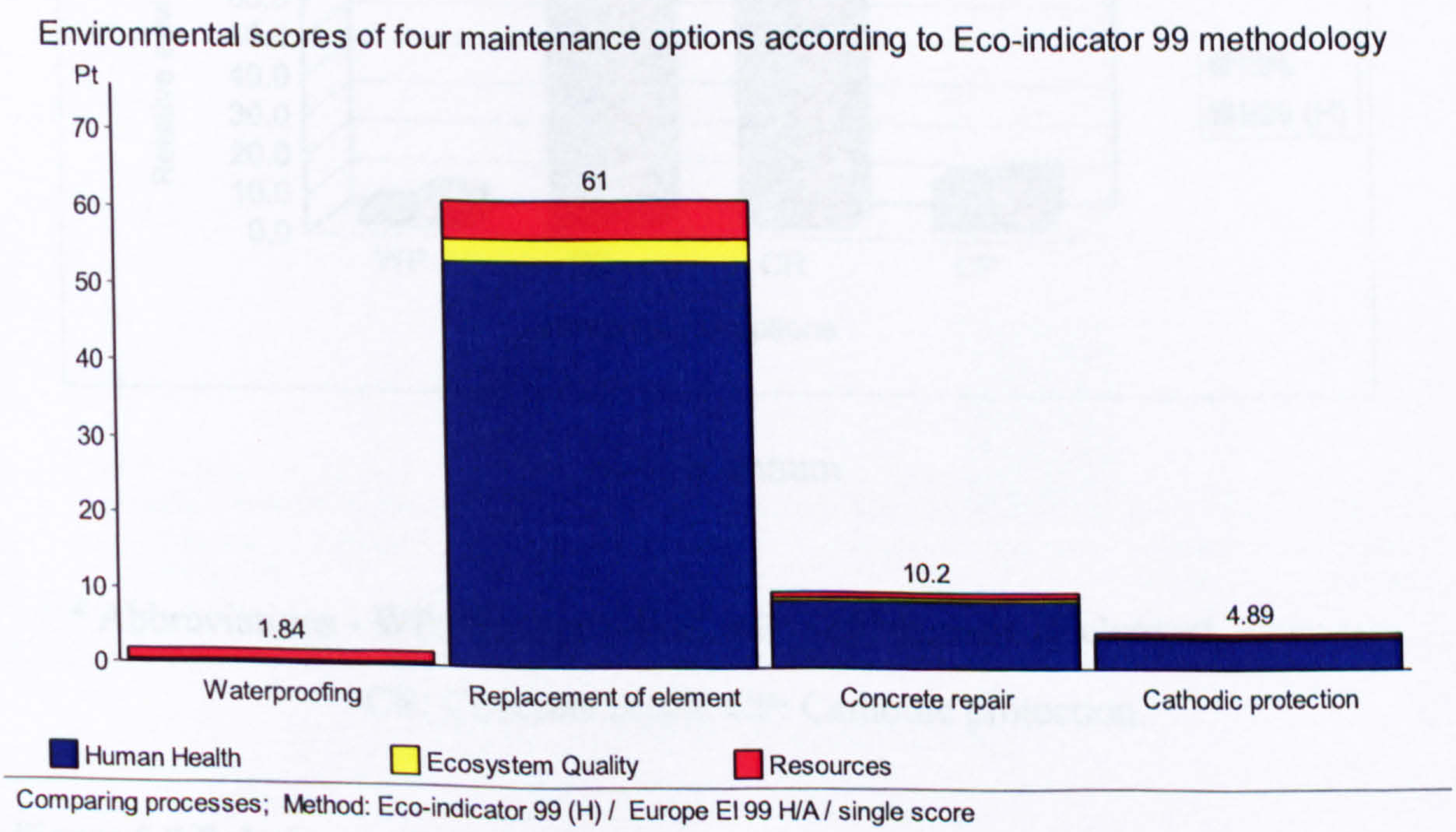
The alternative maintenance options considered for RC slab bridge structure are: concrete repair, replacement of element, cathodic protection and waterproofing. The amount of material input, electricity use and/or waste disposal are estimated based on some assumptions and a review of the literature. Corresponding environmental scores are calculated using the SimaPro program database. The resulting values are used herein as an illustrative exercise.

Figure 5.6 shows the environmental scores of the four maintenance options considered according to Eco-indicator 95 and Eco-indicator 99 (Hierarchist perspective, averaged weighting factors). Here, it is assumed that hierarchist perspective reflects the decision making practice for bridge maintenance activities well because the organisations which are responsible for bridge maintenance such as the central/local governments and the highways agency etc. have hierarchical system. Assumptions and unit environmental data used to quantify these values can be found in Appendix A.

The two methodologies use different normalisation and weighting factors, hence the environmental scores of the four maintenance options are shown on different scales. In order to compare their relative differences, their percentages against the values associated with the 'replacement of element' option are calculated and illustrated in Figure 5.7(a). In turn, their values are divided by their effective lives in order to compare environmental impacts produced per annum. In doing so, it is assumed that the effective lives of waterproofing, replacement of element, concrete repair and cathodic protection are 20, 50, 10 and 30 years, respectively. Figure 5.7(b) shows their relative environmental scores per annum.

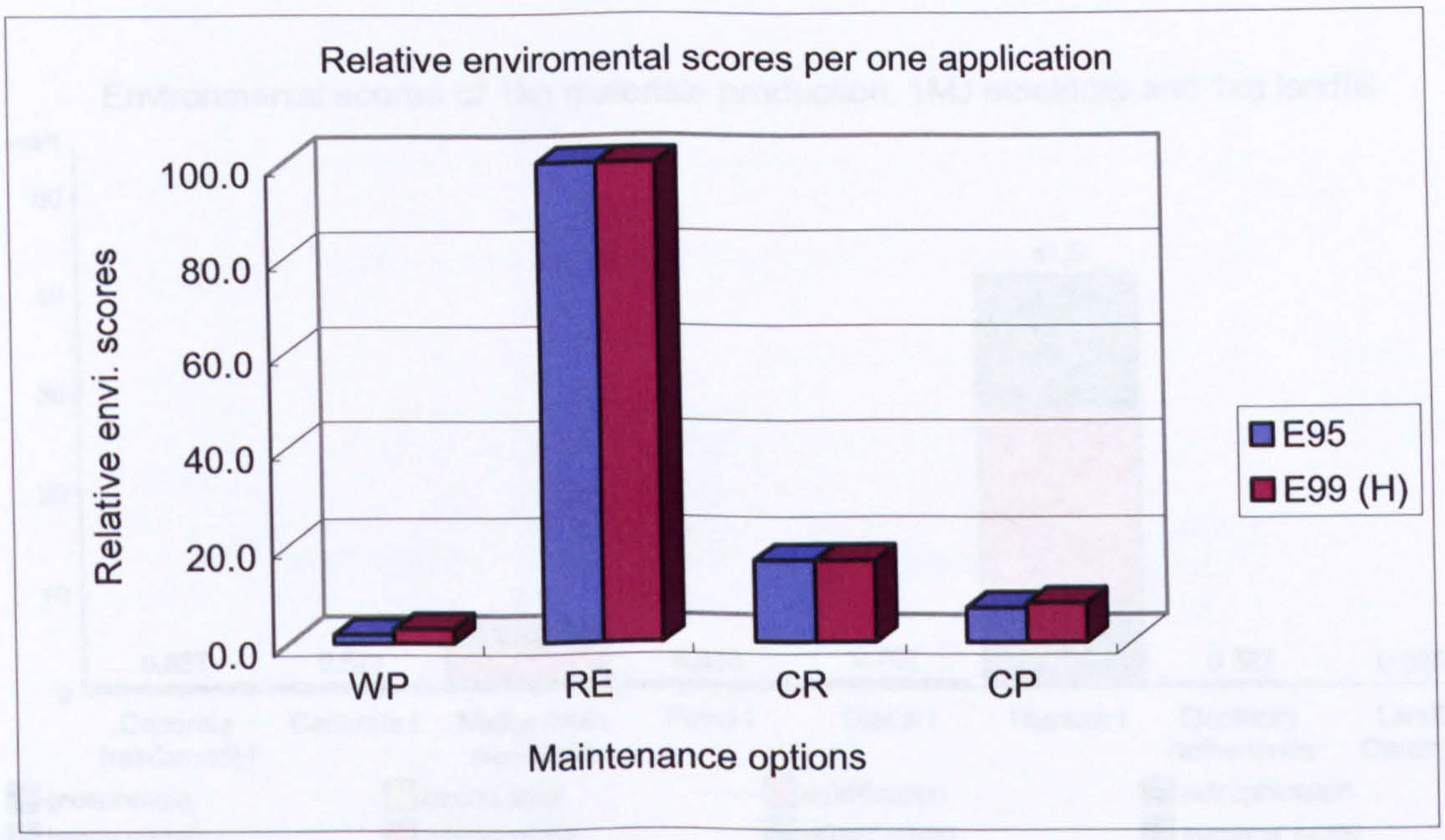


(a) Eco-indicator 95 methodology

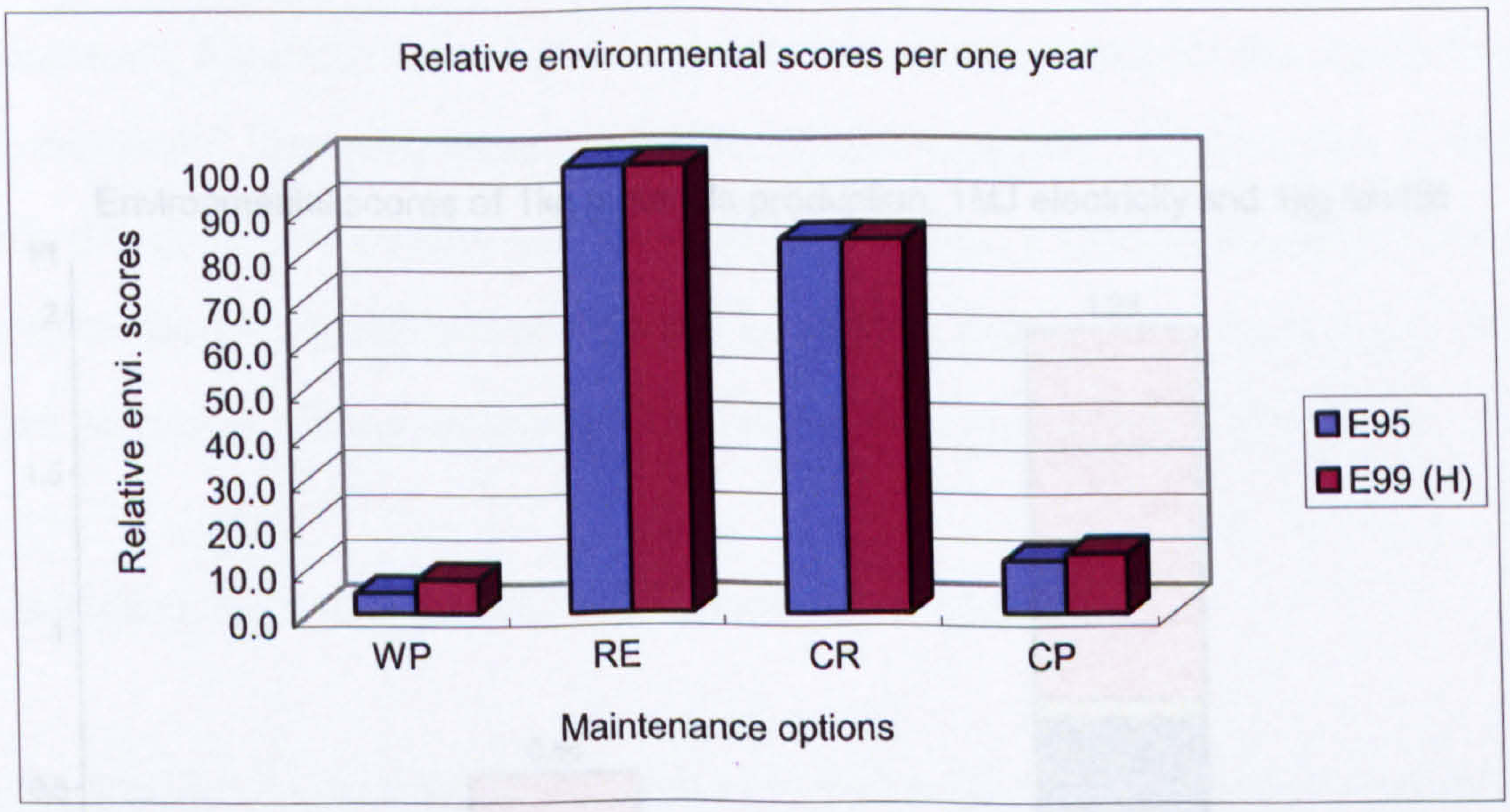


(b) Eco-indicator 99 methodology

Figure 5.6 Environmental scores of four maintenance options



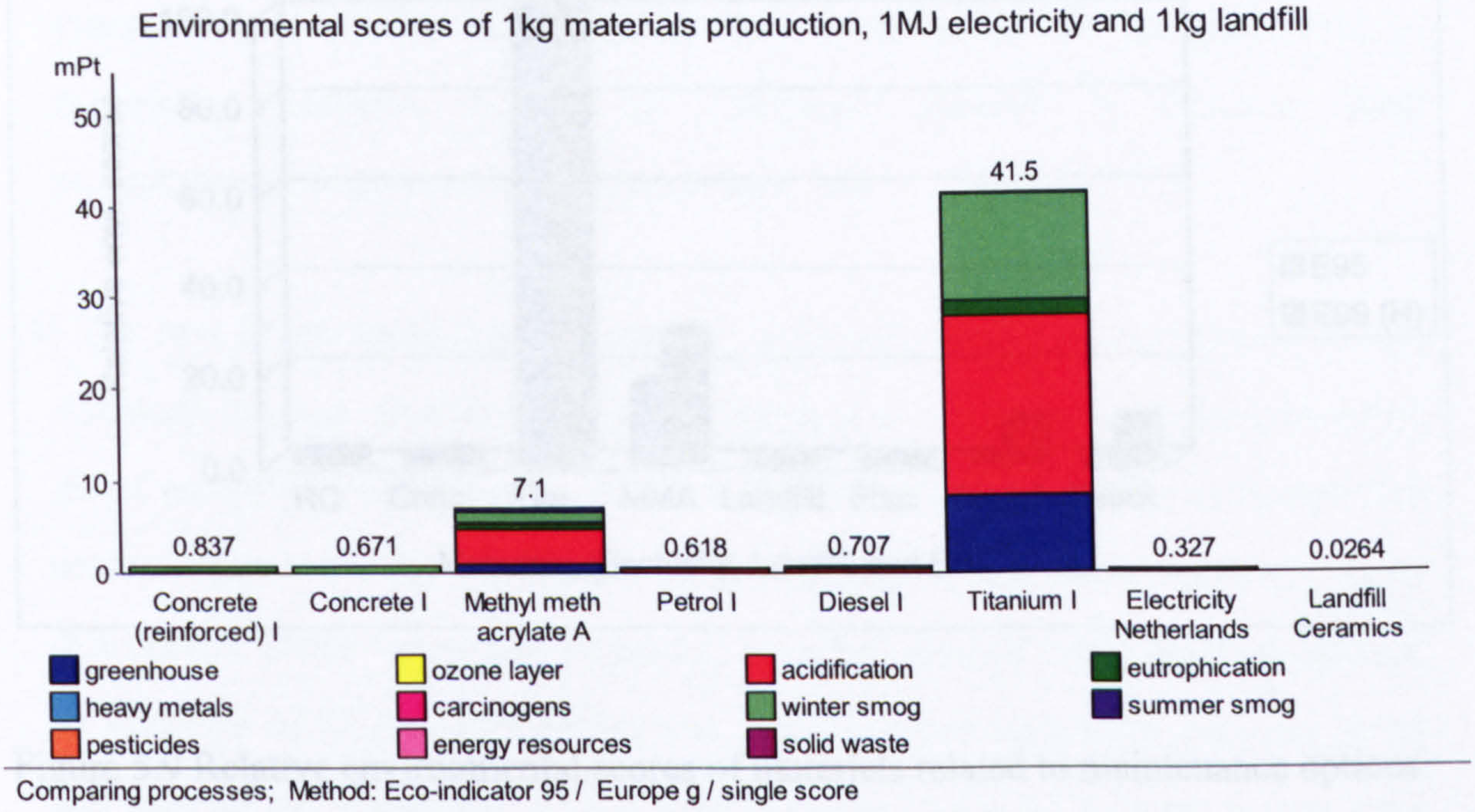
(a) Per application



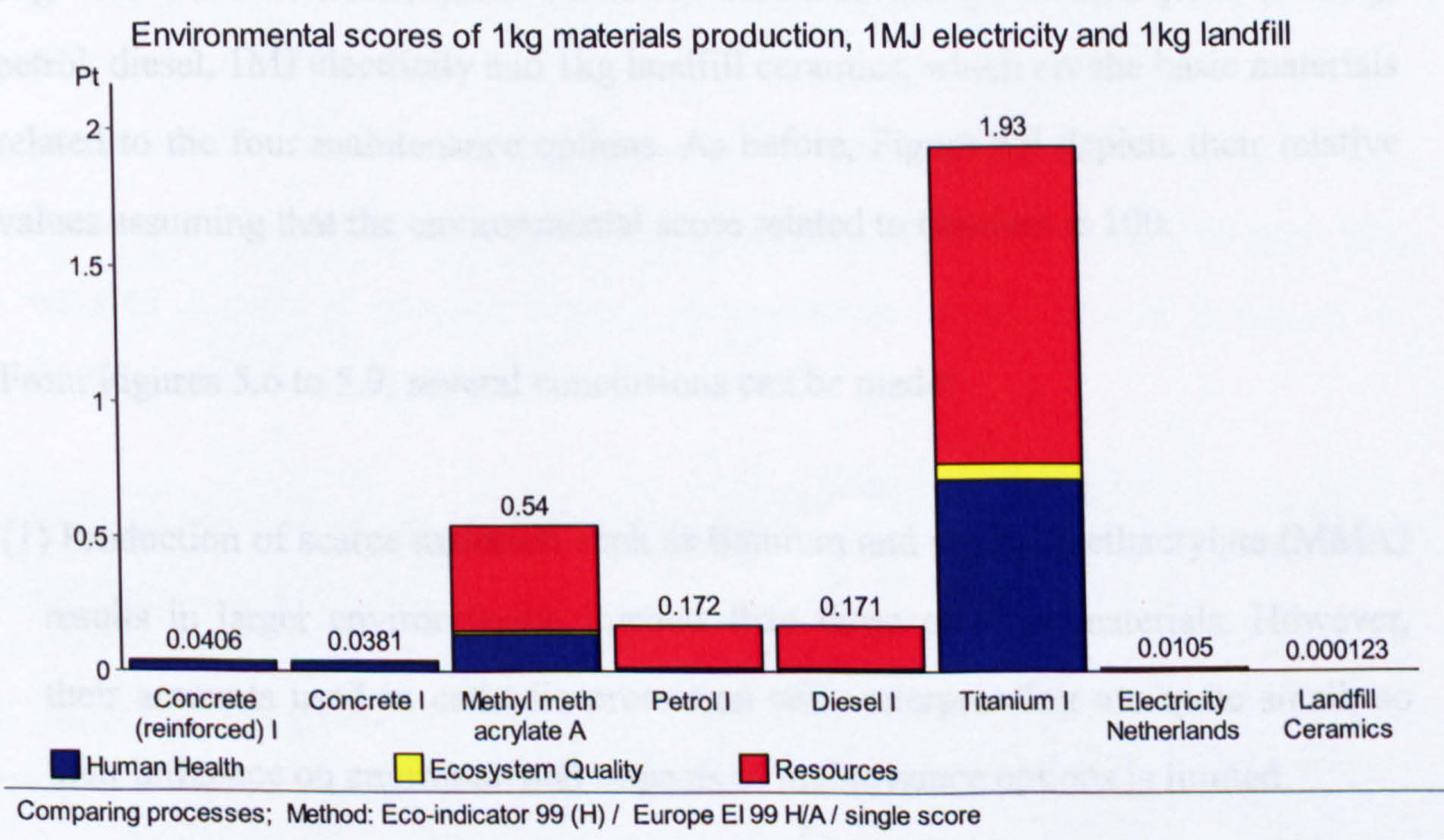
(b) Per annum

* Abbreviations - WP: Waterproofing, RE: Replacement of element, CR: Concrete repair, CP: Cathodic protection.

Figure 5.7 Relative environmental scores of four maintenance options assuming that the environmental score of 'replacement of element' is equal to 100.



(a) Eco-indicator 95 methodology



(b) Eco-indicator 99 methodology

Figure 5.8 Unit environmental scores of materials related to maintenance options

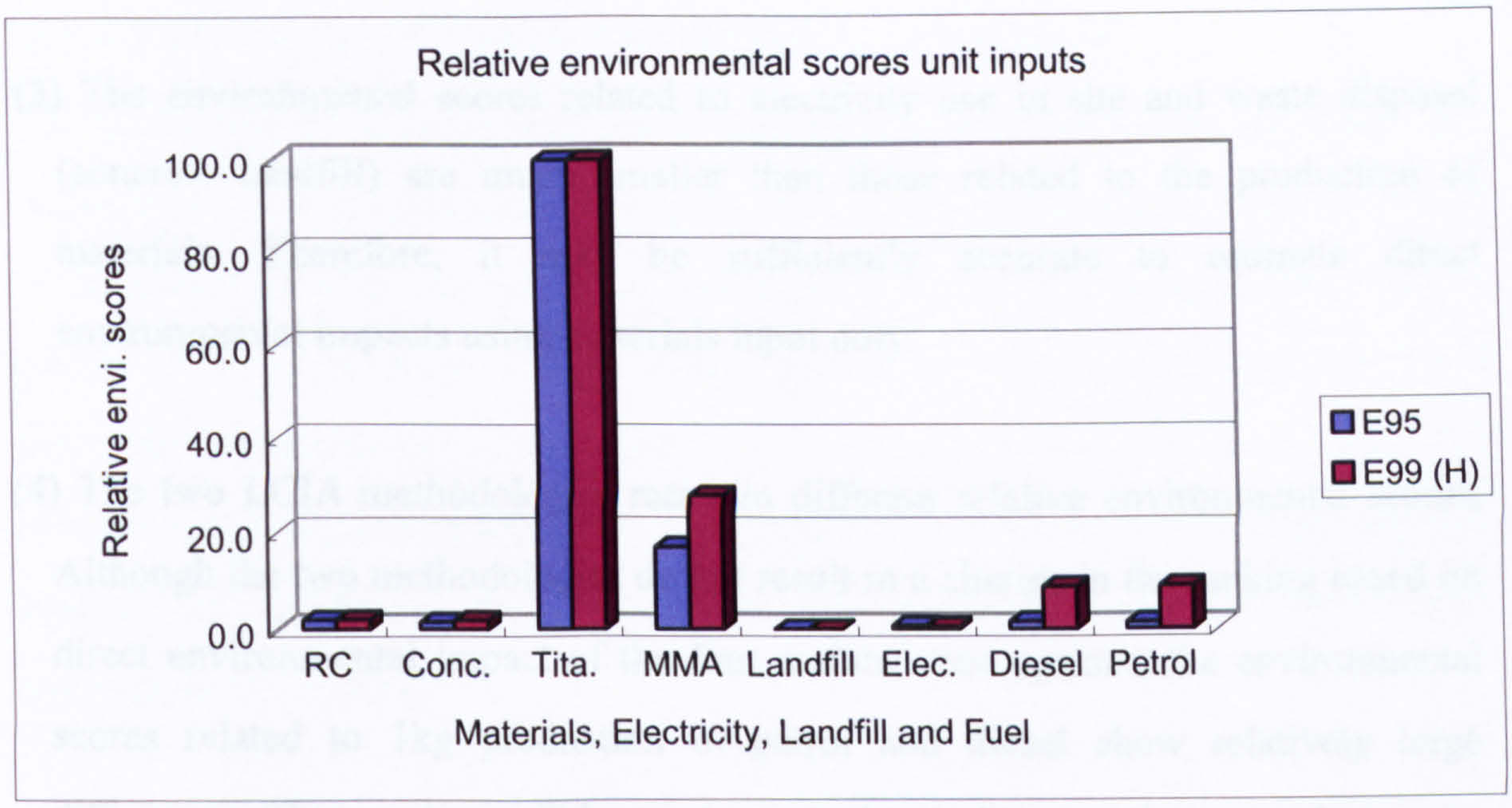


Figure 5.9 Relative environmental scores of materials related to maintenance options

Furthermore, Figure 5.8 shows the single environmental scores for the production of 1kg reinforced concrete, plain concrete, titanium, methyl methacrylate (MMA), petrol, diesel, 1MJ electricity and 1kg landfill ceramics, which are the basic materials related to the four maintenance options. As before, Figure 5.9 depicts their relative values assuming that the environmental score related to titanium is 100.

From Figures 5.6 to 5.9, several conclusions can be made:

(1) Production of scarce materials such as titanium and methyl methacrylate (MMA) results in larger environmental impacts than those of other materials. However, their amounts used in cathodic protection and waterproofing are quite small, so their influence on environmental impacts of maintenance options is limited.

(2) 'Replacement of element' and 'concrete repair' options have larger environmental scores than 'waterproofing' and 'cathodic protection'. The main reason for this is that the former two options require a larger amount of material input than the latter two options.

(3) The environmental scores related to electricity use in site and waste disposal (concrete landfill) are much smaller than those related to the production of materials. Therefore, it may be sufficiently accurate to estimate direct environmental impacts using materials input only.

(4) The two LCIA methodologies result in different relative environmental scores. Although the two methodologies do not result in a change in the ranking based on direct environmental impact of the four maintenance options, the environmental scores related to 1kg production of petrol and diesel show relatively large differences. These values will be used to calculate indirect environmental impacts, so selection of LCIA methodology can affect relative magnitude between direct and indirect environmental impacts. For example, Table 5.12 shows approximate amounts of petrol and diesel which produce indirect environmental impacts equivalent to the direct impacts of four maintenance options. Clearly, large differences in absolute terms are present when comparing the two methodologies (Eco-indicator 95 and Eco-indicator 99). On average, the Eco-indicator 95 is five times less onerous than the Eco-indicator 99. This might be a reflection of the increasing importance attributed to CO_2 emissions in recent years. The approach adopted in order to quantify indirect environmental impacts will be discussed in the next section.

Table 5.12 Amounts of petrol and diesel whose environmental impacts are equivalent to direct impacts of four maintenance options

Maintenance Options	Eco-indicator 95		Eco-indicator 99	
	Petrol (kg)	Diesel (kg)	Petrol (kg)	Diesel (kg)
Waterproofing	39	34	11	11
Replacement of element	2087	1825	355	357
Concrete repair	350	306	59	60
Cathodic protection	147	128	28	29

5.5.4 Calculation of indirect environmental impacts

The environmental impacts from traffic disruption arise mainly from additional fuel consumption due to increased journey time and/or journey distance. Recently, some LCA studies tried to include road traffic noise [183] or environmental impacts related to the replacement of tires, battery and oil for passenger vehicles [184], but their methodologies do not appear well developed and, in any case, the environmental impacts in works site are negligible. Therefore, in this study only the amount of additional fuel consumption is calculated and converted into environmental impacts.

The formulae to calculate the amount of fuel consumption is similar to those used for the calculation of vehicle operating cost from the fuel consumption explained in the section 4.2.2. According to the COBA manual [142], the amounts of fuel used by various vehicle classes can be calculated by using the parabolic formula given below using the fuel usage parameter values.

$$C=a+bV+cV^2 \qquad (5.2)$$

where, C=the fuel used in litres per kilometre per vehicle

V= average link speed in kilometres per hour

The coefficients for five vehicle categories for fuel consumption are shown in Table 5.13 and the resulting parabolic functions are illustrated in Figure 5.10.

Table 5.13 Fuel usage 2002 parameter values (litres/km) ([142])

Vehicle Category	Fuel consumption coefficients		
	a	b	c
Cars	0.1576	-0.0028	0.00001933
Light Goods Vehicles (LGV)	0.2148	-0.0038	0.00002934
Other Goods Vehicles (OGV1)	0.5696	-0.0096	0.00007778
Other Goods Vehicles (OGV2)	1.3100	-0.0206	0.00016302
Buses & Coaches (PSV)	0.6270	-0.0115	0.00009317

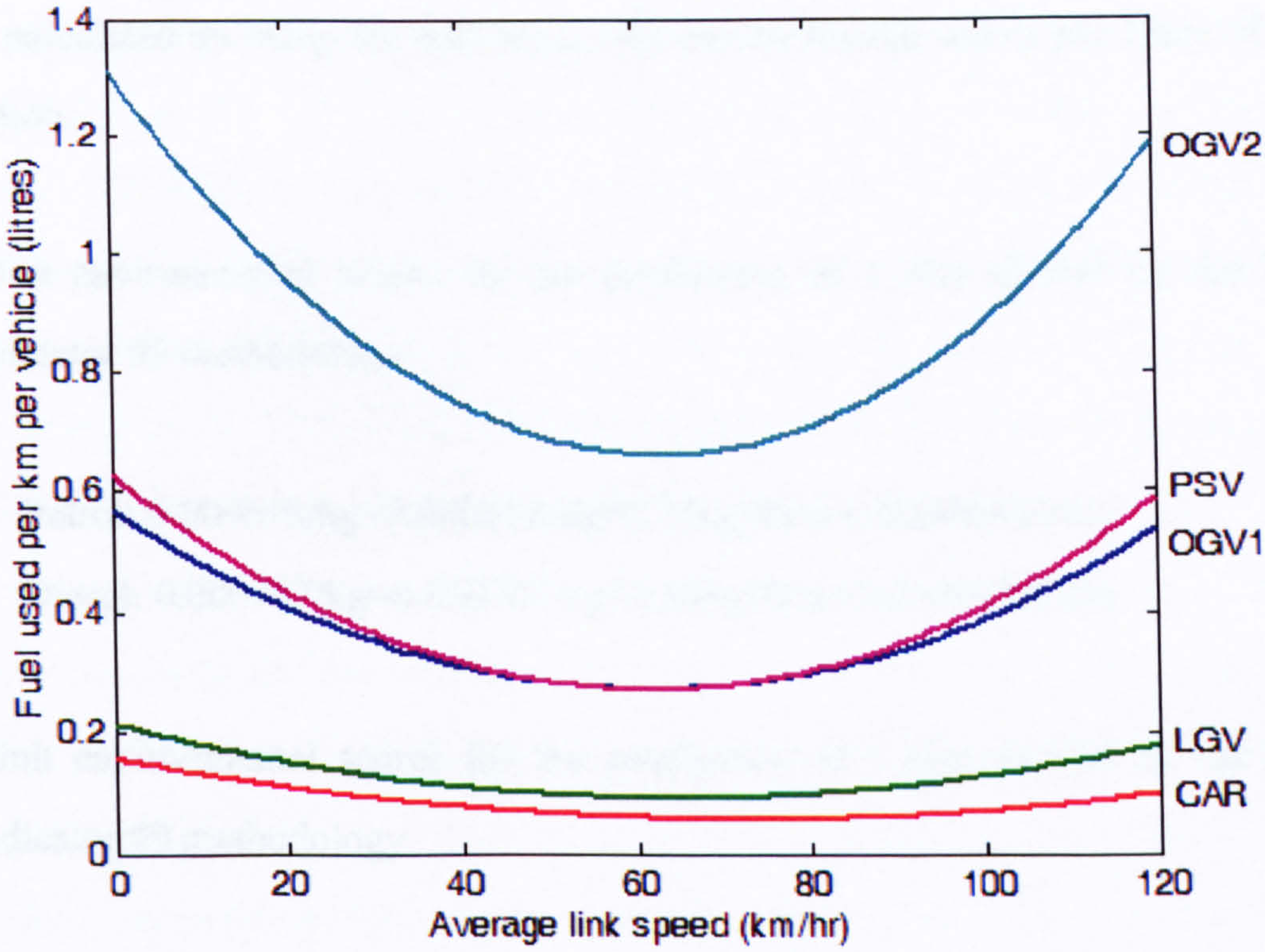


Figure 5.10 Fuel consumption variations of five vehicle types due to vehicle speed

Application of the above equation calculates the fuel used in litres per kilometre in 2002. COBA adjusts these parameters over time to reflect the predicted changes in fuel efficiency and also, for cars, the changes in the proportion of the vehicle fleet using either petrol or diesel. The annual percentage changes in fuel usage per kilometre are given in Table 5.14.

Table 5.14 Compound annual growth rates in fuel consumption (% per annum) ([142])

Years	Vehicle Type				
	Cars	LGV	OGV1	OGV2	PSV
Annual Changes (%pa)					
2002-2010	-2.88	-1.35	-1.0	-1.0	0
2010-2031	-0.54	0	0	0	0
2031-2099	0	0	0	0	0

The amount of net fuel consumption due to bridge maintenance activities can be calculated by subtracting the amount of fuel consumption in the absence of site works from those in the presence of site works. Hence, indirect environmental scores can be calculated by using the following unit environmental scores per 1litre of fuel production.

1) Unit environmental scores for the production of 1 litre of fuel by the Eco-indicator 95 methodology

   Petrol: 0.000618/kg=0.000618/kg*0.75kg/litre=0.0004635/litre
   Diesel: 0.000707/kg=0.000707/kg*0.84kg/litre=0.0005939/litre

2) Unit environmental scores for the production of 1 litre of fuel by the Eco-indicator 99 methodology

   Petrol: 0.172/kg=0.172/kg*0.75kg/litre=0.129/litre
   Diesel: 0.171/kg=0.171/kg*0.84kg/litre=0.144/litre

The unit environmental scores shown above are related to the production of fuels based on Eco-indicator 95 and Eco-indicator 99 methodologies. These two approaches cannot be compared with each other because two LCIA methodologies assumed different characterisation, normalisation and weighting factors in calculating the environmental score. However, as can be seen in Figure 5.9 and Table 5.12, the selection of Eco-indicator 99 methodology would have an effect of increasing the proportion of indirect environmental impacts among the total impacts.

In this study, it is assumed that vehicle type 'Car' consumes petrol, whereas the other vehicle types consume diesel.

5.6 Conclusions

The general characteristics of LCA methodology and its application to the construction industry products and processes were reviewed in this chapter. Furthermore, the environmental impacts related to bridge management activities were identified. More specifically, the direct impacts of four maintenance options for reinforced concrete slab bridge structure were quantified based on the Eco-indicator 95 and Eco-indicator 99 methodology. The method for evaluating the indirect impacts associated with additional fuel consumption due to traffic disruption was also presented. The illustrative environmental data presented in this chapter are used in the case studies given in Chapter 7, where their influence on the choice of a maintenance plan optimized against cost and sustainability criteria is presented in more detail. In summary, this study uses LCA results as a component of a tool, developed to support sustainable development decisions in bridge maintenance activities. Throughout this work emphasis is placed on the requirements for integrating cost and sustainability objectives within a decision framework subject to uncertainty; the LCA results presented in this chapter should be seen in that context, rather than as quantitative values of the relevant environmental indicators. For an in-depth approach to LCA in highway maintenance the reader is referred to the recent studies by Elghali [185, 186].

Chapter 6

Development of a quantitative methodology

6.1 Main functions

6.1.1 Introduction

The main purpose of this study is to develop a quantitative methodology to combine WLC and LCA under uncertain conditions in order to embody the concepts of sustainability in bridge management. From a literature review, it is apparent that in order to meet this objective several methodologies such as generation of maintenance plans, WLC, LCA, MCDA and probabilistic modelling should be appropriately integrated. Furthermore, not only direct impacts arising from maintenance work itself but also indirect impacts related to traffic disruption should be quantified in order to evaluate total impacts associated with bridge maintenance activities.

As a quantitative tool which brings the above methods and requirements together, a computer program has been developed using 'FORTRAN' programming language. The program developed can undertake deterministic and/or probabilistic analysis according to user preference. Figures 6.1 and 6.2 show the main flow of deterministic and probabilistic analyses, respectively. In general, the probabilistic analysis follows the same procedures as the deterministic analysis except that the former encompasses some additional procedures and techniques such as random sampling, convergence check and evaluation of statistical properties of the output. The detailed flow charts for the software tool developed in this study are given in

Appendix B in order to show how the various components fit together and form a stand-alone program.

In the next sections, the main functions of deterministic and probabilistic analysis are described in more detail.

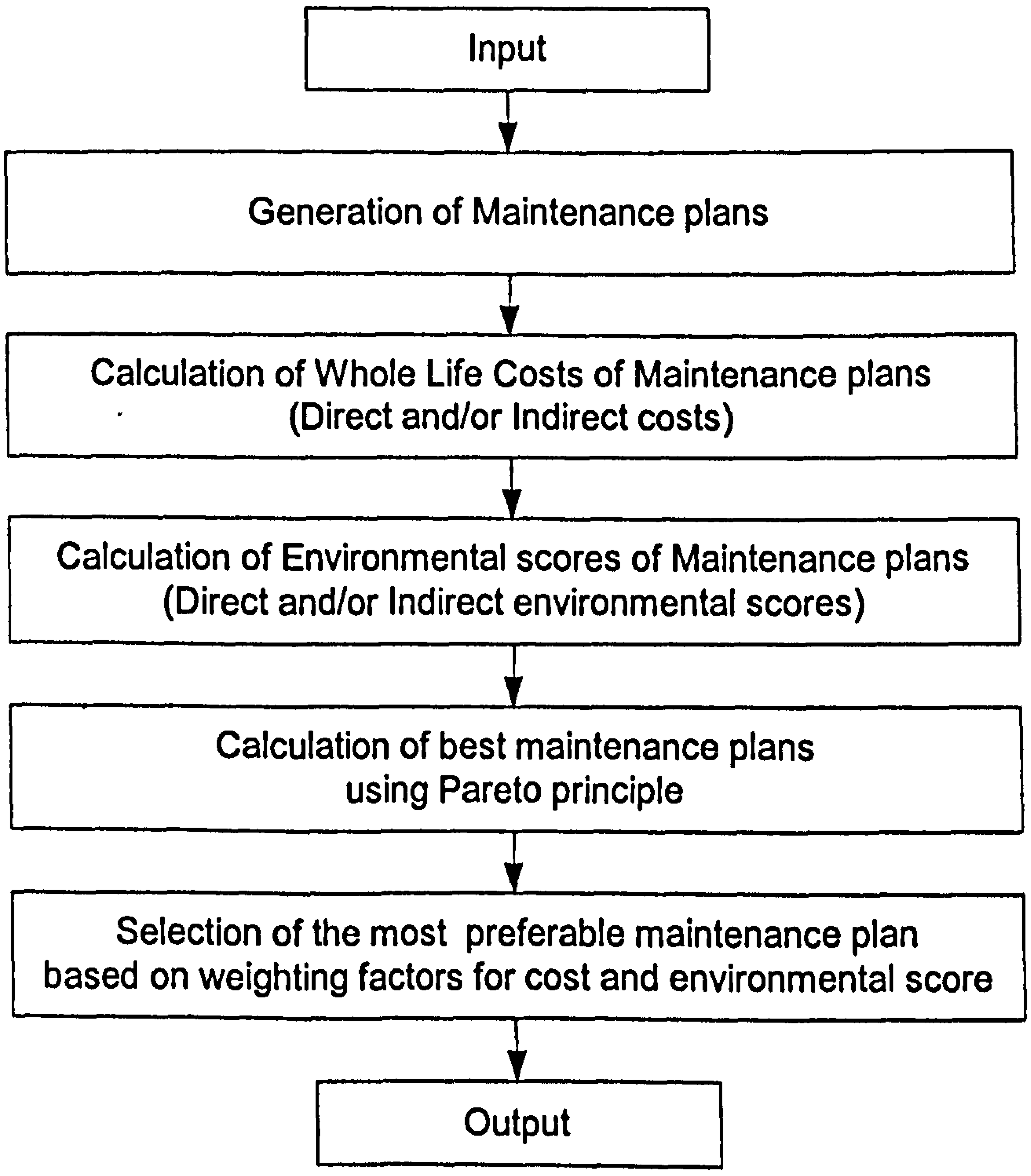


Figure 6.1 Main flow of deterministic analysis

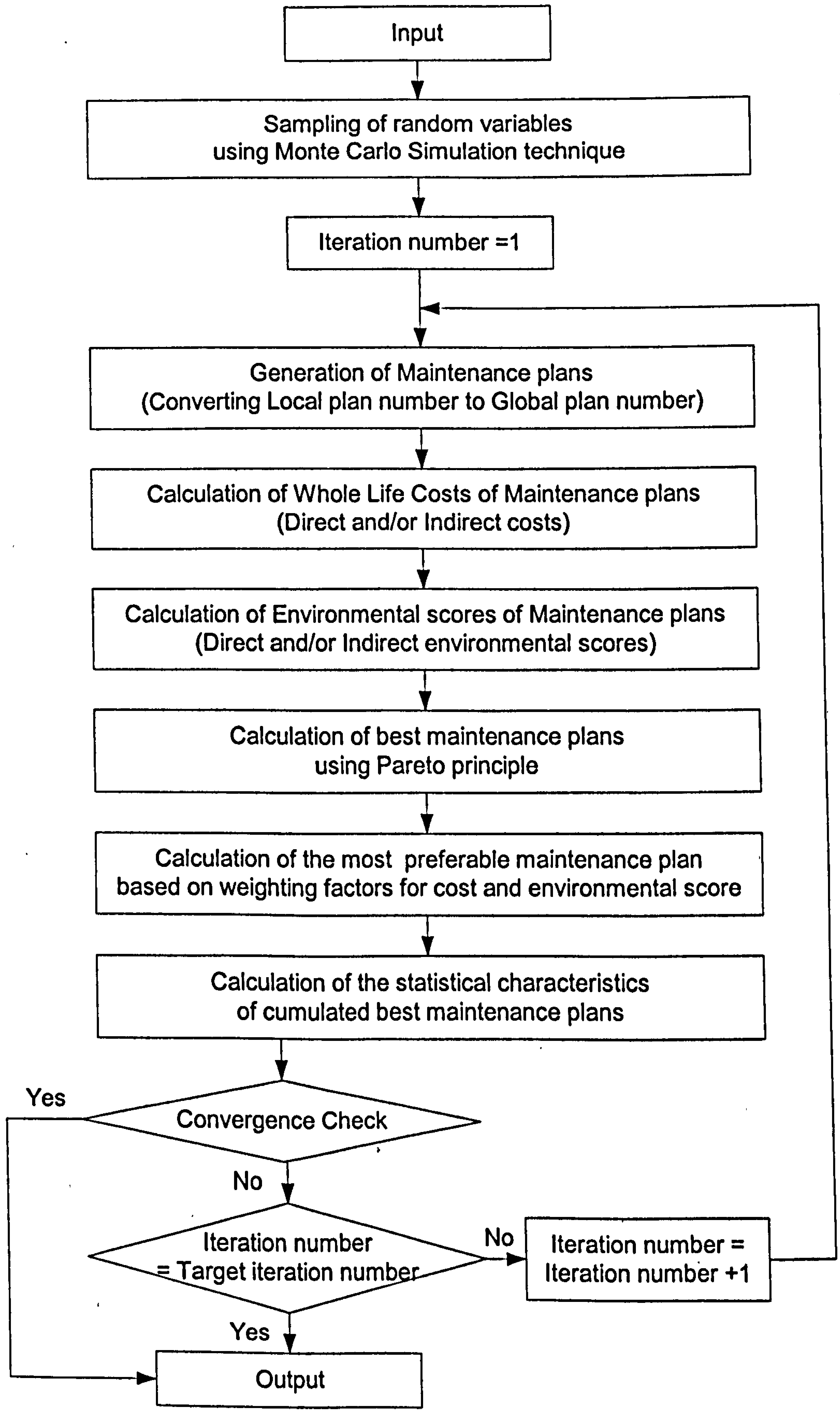


Figure 6.2 Main flow of probabilistic analysis

6.1.2 Deterministic analysis

1) Generation of maintenance plans

All feasible maintenance plans are generated based on a time based approach and/or a performance based approach.

The effective life concept, explained in the section 3.2.2, is associated with a time based approach. The maintenance plans are generated based on the effective lives of maintenance options irrespective of the actual performance profile of the structure under maintenance.

On the other hand, a performance index approach, presented in the section 3.2.3, combines time and performance based approaches. Hence, the preventative maintenance options are applied repeatedly at the end of their effective lives as long as the performance profile is above the target/allowable level and the essential maintenance options are applied at the point where the performance profile crosses the target/allowable value.

The program developed in this study has a function to generate the maintenance plans based on either an effective life concept or a performance index approach, so the analyst can choose the method according to his/her preference and data availability.

Moreover, compared to earlier research, the program provides an improved ability for generating maintenance plans. In previous research [64, 76, 128], maintenance plans were created by applying repeatedly the same maintenance option. This approach is only useful for comparing the performances of different maintenance options in extending the service life of the structure. It does not consider the realistic possibility that the best maintenance plan in terms of, for example, minimum cost may be obtained by mixing different maintenance options. To overcome this limitation, this study allows the combination of all maintenance options considered and thus generates all feasible maintenance plans. One example of the application of the developed methodology can be found in Figure 6.4 in section 6.2.

Some fundamental assumptions are used in generating maintenance plans. It is assumed that maintenance options can be chosen alternatively to treat bridge structure's specific deterioration problem. However, it is also assumed that they are not applied together at the same time. Only one maintenance option is applied at any one time. In other words, the application of any subsequent maintenance option is delayed until the effective life of the current maintenance option elapses or a target safety condition is violated.

The specific methodologies adopted in this study related to generating maintenance plans based on an effective life concept and a performance index approach are described in more detail in section 6.2.2.

2) Calculation of whole life costs of maintenance plans.

Each maintenance plan is composed of several maintenance options undertaken at different future times. The direct and indirect costs of each maintenance option are calculated based on direct cost data and some additional data which are used to quantify the traffic management as a result of the particular maintenance option considered. All costs are discounted to net present values pertaining to a specified reference year. Through the same process, present values of direct and indirect costs of all the constituent maintenance options are calculated, and hence the total cost of a maintenance plan can be evaluated. In calculating the total cost, different weighting factors can be applied to the direct and indirect cost components. It is thus possible to also consider the two extreme cases of (a) direct and (b) indirect costs only.

3) Calculation of environmental scores of maintenance plans.

Environmental scores of maintenance plans are calculated based on processes similar to those used for calculating costs. Direct environmental scores are calculated based on the inputted direct environmental scores of maintenance options. On the other hand, indirect environmental scores are calculated by converting amounts of additional fuel consumptions due to traffic disruption into environmental scores. For this, environmental scores for unit fuel consumption, i.e. consumption of 1 litre petroleum or diesel, should be given. Environmental scores of a maintenance plan can be evaluated by adding environmental scores of constituent maintenance options. However, in contrast to costs, no discounting is applied [187, 188]. As with costs, the inclusion of direct and indirect environmental scores in calculating total environmental scores is controlled by weighting factors for direct and indirect environmental scores.

4) Identification of best maintenance plans using Pareto principle

Based on the total costs and environmental scores of all maintenance plans, several best maintenance plans on the non-inferior curve (see Figure 2.3) are identified using the Pareto principles.

If the total number of the generated maintenance plans is m, the program executes $m \times (m-1)$ times pair-wise comparison between two maintenance plans. During each comparison, if the cost and environmental score of one maintenance plan are both larger than those of another plan, the former is considered to be dominated by the latter and is excluded from subsequent comparisons. Thus, through the full process, only maintenance plans which are not dominated by others are identified and retained for further consideration.

5) Selection of the optimal maintenance plan based on the decision maker's preference on cost and environmental score

If there is more than one maintenance plan on the non-inferior curve, the most preferable maintenance plan can be decided based on the decision maker's preference on cost and environmental score. In this study, this preference is represented by two weighting factors for cost and environmental score respectively, whose sum is equal to unity.

The program developed in this study provides two different approaches for relating weighting factors for cost and environmental score with an optimal maintenance plan.

The first approach is to find a most preferable maintenance plan for the weighting factors given by the decision maker. If a weighting factor for cost is given by the decision maker, the program calculates the weighting factor for environmental score by subtracting the weighting factor for cost from unity. As shown in formula (2.3), these weighting factors are multiplied with the normalised cost and environmental score of the maintenance plans on the non-inferior curve. Then the maintenance plan which has the minimum overall weighted score is selected as the most preferable one. The program developed in this study allows arbitrary number of weighting factors for cost to be specified, so the decision maker can check the variation of an optimal maintenance plan against the different weighting factors for cost and environmental score.

Another approach is to find the range of weighting factors for cost and environmental score which make each maintenance plan on the non-inferior curve optimal. This approach is developed based on the idea that the different maintenance plans on the non-inferior curve can be optimal within different range of weighting factors for cost and environmental score. The process for this calculation is explained below. If it is assumed that three consecutive points are on the non-inferior curve as shown in Figure 6.3, their overall weighted scores for preference can be calculated by the following formulae, respectively, based on formula (2.3).

$$S_{i-1} = w_E s_{Ei-1} + w_C s_{Ci-1} = (1-w_C)s_{Ei-1} + w_C s_{Ci-1} = w_E s_{Ei-1} + (1-w_E)s_{Ci-1}$$

$$S_i = w_E s_{Ei} + w_C s_{Ci} = (1-w_C)s_{Ei} + w_C s_{Ci} = w_E s_{Ei} + (1-w_E)s_{Ci}$$

$$S_{i+1} = w_E s_{Ei+1} + w_C s_{Ci+1} = (1-w_C)s_{Ei+1} + w_C s_{Ci+1} = w_E s_{Ei+1} + (1-w_E)s_{Ci+1}.$$

If the middle point P_i represents the optimal maintenance plan, its overall weighted score for preference should be less than those of neighboring two points. Namely,

$S_i \le S_{i-1}$, $S_i \le S_{i+1}$

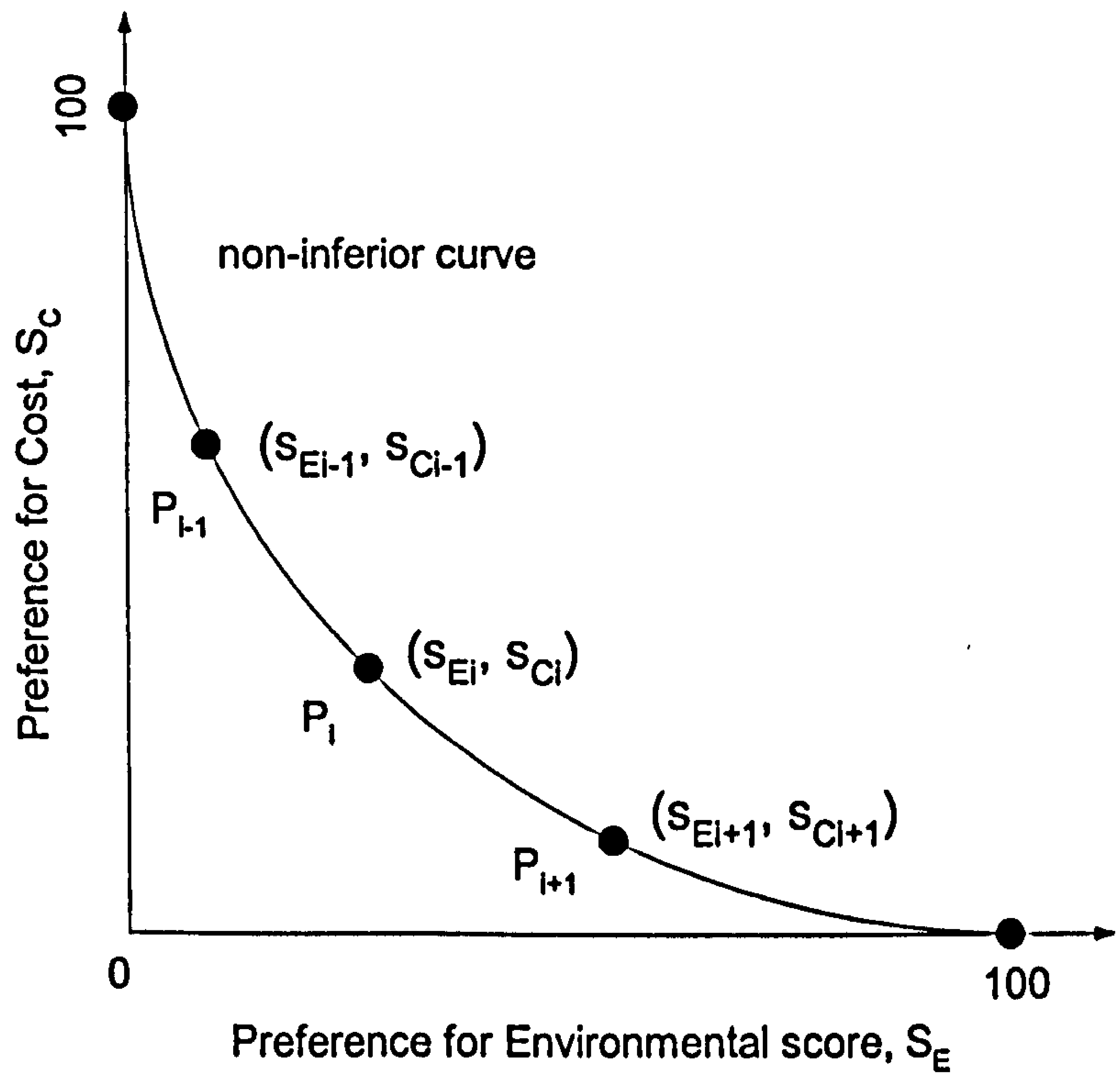


Figure 6.3 Three consecutive maintenance plans on the non-inferior curve

The range of weighting factor for cost and environmental score satisfying these conditions can be found by inserting S_{i-1} S_i, and S_{i+1} values into above relations. The results are:

$$\frac{s_{Ei+1} - s_{Ei}}{s_{Ei+1} - s_{Ei} + s_{Ci} - s_{Ci+1}} \le w_C \le \frac{s_{Ei} - s_{Ei-1}}{s_{Ei} - s_{Ei-1} + s_{Ci-1} - s_{Ci}} \qquad (6.1)$$

$$\frac{s_{Ci-1} - s_{Ci}}{s_{Ei} - s_{Ei-1} + s_{Ci-1} - s_{Ci}} \le w_E \le \frac{s_{Ci} - s_{Ci+1}}{s_{Ei+1} - s_{Ei} + s_{Ci} - s_{Ci+1}} \qquad (6.2)$$

Based on the above formula, the program developed automatically calculates the range of weighting factors for cost and environmental score in deterministic analysis and also in each iteration of probabilistic analysis.

In summary, the above two approaches can be used in deterministic as well as probabilistic analysis. However, it is considered that the former approach is more applicable in the probabilistic analysis because the variation of frequencies of optimal maintenance plans according to the weighting factors can be easily counted using this approach. On the other hand, the latter approach is considered to be more useful in the deterministic analysis in that the whole range of weighting factors for cost and environmental score which make each maintenance plan optimal can be quantified.

6.1.3 Probabilistic analysis

1) Generation of probabilistic variables using Monte Carlo Simulation technique

In previous chapters 3, 4 and 5, it is argued that the methodologies and input quantities needed to quantify/evaluate sustainable bridge management such as development of maintenance plans, WLC and LCA have inherent uncertainties. The principal uncertainty sources in each methodology, and tools appropriate for their modelling, have also been reviewed.

Different tools have been developed to address different types of uncertainty. In broad terms, they can be classified into three groups: tools aimed at an increase of data quality, tools for sensitivity analysis and tools for tackling random variability (see Table 5.11). Monte Carlo simulation technique has been commonly used as a tool for uncertainty analysis due to random variability discussed in previous probabilistic WLC and LCA studies. Taking this into account, in this study the Monte Carlo simulation technique is also chosen as a tool to tackle the uncertainty in sustainable bridge management. Previous information on modelling of random variables pertinent to bridge maintenance and life cycle analysis has been reviewed in Chapters 3, 4 and 5. Based on the review, eight representative probabilistic shapes are selected and programmed in this study. The probabilistic distribution shapes and their defining factors are presented in Table 6.1. If necessary, other probabilistic distribution shapes can be easily added to the developed program. This study relied on several references [189-193] for understanding the characteristics of probabilistic distribution functions, but their details are not described here.

Table 6.1 Probabilistic distribution shapes included in the program

Name	Abb.	Defining factors
Uniform	UNI	factor1=minimum, factor2=maximum
Triangular	TRI	factor1=minimum, factor 2=mode, factor3=maximum
Normal	NOR	factor1=mean, factor2=standard deviation
Lognormal	LNO	factor1=mean of Lognormal distribution factor2=standard deviation of Lognormal distribution
Lognormal2	LN2	factor1=mean of corresponding normal distribution factor2=standard deviation of corresponding normal distribution
Truncated Normal	TNO	factor1=mean, factor2=standard deviation, factor3=lower limit, factor4=upper limit
Truncated Lognormal	TLN	factor1=mean of Lognormal distribution factor2=standard deviation of Lognormal distribution factor3=lower limit, factor4=upper limit
Truncated Lognormal2	TN2	factor1=mean of corresponding normal distribution factor2=standard deviation of corresponding normal distribution, factor3=lower limit, factor4=upper limit

The use of the program developed for sensitivity analysis, which requires change of a single input parameter, is also relatively straightforward. However, tools to quantify/evaluate data quality are not included in the developed program assuming that this activity is undertaken as part of a more general research effort aimed at improving WLC and LCA predictions.

In summary, the program developed in this study uses the Monte Carlo simulation technique to account for randomness in the input data and to quantify its impact on the choice of the best maintenance plan.

2) Execution of analysis

During each iteration of probabilistic analysis, all the steps in a deterministic analysis are executed. In probabilistic analysis, the concept of a global plan number is used, so that if the same maintenance plan is generated in different iterations arising from different samples, it is deemed to be the same plan. In other words, if maintenance plans generated in different iterations are identical in terms of composition and order of maintenance options, they are given the same global plan number. The relative frequencies of best maintenance plans are also counted using the global plan number.

3) Convergence check

In probabilistic analysis, it is necessary to check whether the analysis results are converging as the iterations increase. The program developed produces various results, and it is necessary to select appropriate output quantities for checking convergence. The program currently focuses on the statistical properties and distribution shapes of total costs and environmental scores of cumulated optimal maintenance plans. The process used in this study is explained in more detail below.
As the iteration number representing the sample size increases, the optimal maintenance plans are collected. If the sample is sufficient, the statistical characteristics of total costs and environmental scores of the cumulated optimal maintenance plans are expected to converge. The characteristics are here represented by the minimum, maximum, mean and standard deviation. In other words, the chosen control criteria are related to first and second moment properties of the (unknown) distribution of costs and environmental scores. If the differences in these four quantities in consecutive iterations are within a specified error limit, it can be said that there is evidence of convergence. If convergence is maintained over a number of consecutive iterations, it may be postulated that global convergence has been reached. More specifically, convergence is checked by the following criteria:

(1) In each iteration, the minimum, maximum, mean and standard deviation values of total costs and environmental scores of cumulated optimal plans are calculated.

(2) The relative errors in the four parameters in two consecutive iterations (namely, i_{th} and $(i+1)_{th}$ iterations) are calculated by

Relative error = ((i+1)$_{th}$ value – i$_{th}$ value)/i$_{th}$ value.

(3) If the relative errors are within specified error limit (namely, CP: convergence percentage), a first indication of convergence is obtained.

(4) If above (1)-(3) steps happen consecutively for a number of specified times (namely, CN: convergence number), it is considered that the convergence has been reached and the iterations which represent increasing sample size of the random input parameters are terminated.

(5) If the iteration number reaches the specified sample size in the input file without convergence, the program stops and produces the corresponding results. In this case, it is desirable to increase the sample size and execute the analysis again.

(6) As the CP value gets smaller and the CN value gets larger, additional iterations are required. The analyst can obtain a feel for the 'accuracy' of the overall process by parametrically changing these two values. The effect of CP and CN values on the probabilistic analysis results will be shown with some examples in section 7.4.

4) Calculation of frequency of optimal maintenance plans

The frequencies of optimal maintenance plans are calculated for any given weighting factors for cost and environmental score or for all the maintenance plans on the non-inferior curve.

In this section, the main characteristics of a quantitative methodology have been described. However, the descriptions are not enough to understand the specific data requirement, their role in the analysis and relevant modelling techniques in the developed program. Therefore, in the next section additional explanation associated with the specific functions of the program will be given following the order of input file structure.

6.2 Program structure

The input file comprises five data blocks namely:

- GENERAL DATA;
- MAINTENANCE OPTIONS;
- DIRECT IMPACT;
- INDIRECT IMPACT; and
- WEIGHTING FACTORS.

In each data block a number of variables need to be specified. The full description is presented in Appendix C. In the following the basic assumptions, the associated modelling techniques as well as the most important limitations are highlighted.

6.2.1 General Input data

In this data block, (1) overall analysis controlling parameters, (2) bridge dimensions, (3) reference time and (4) discount rate are specified.

(1) Overall analysis controlling parameters

Analysis type can be selected between deterministic and probabilistic analysis. Likewise, *analysis range* can be confined to direct impacts only or direct plus indirect impacts. The analysis type and analysis range selected affect subsequent data input requirements. In case that the probabilistic analysis option is chosen, additional three input parameters, i.e. *sampling size in the simulation*, *CP* and *CN* values explained in the section 6.1.3, need to be specified for defining convergence criteria in the probabilistic analysis results.

(2) Bridge dimensions

The dimension of bridge structure needs to be specified for calculating indirect impacts and combining them with direct impacts. More specifically, the *width of* *lanes only* is used to adjust the vehicle speed in works site. On the other hand, the *length* and *total width of superstructure* are used to convert indirect impacts calculated for the whole bridge structure into values per unit area, and this makes it possible to combine them with direct impacts which are inputted per unit area.

(3) Time horizon and reference times

Several reference times need to be specified in order to determine the first maintenance timing and the end year of bridge maintenance. The reference times considered in this study are illustrated in Figure 6.4. The first maintenance timing is calculated from the relations of t_0, t_{now} and additional data from an effective life concept or a performance index approach. The method for calculating the first maintenance timing is explained in the next section. On the other hand, the end year of bridge maintenance (t_{end}) is calculated by the following formula. The definitions of t_0, t_{now} and t_{req} are explained in Appendix C.

$$t_{end} = t_{now} + t_{req} \tag{6.3}$$

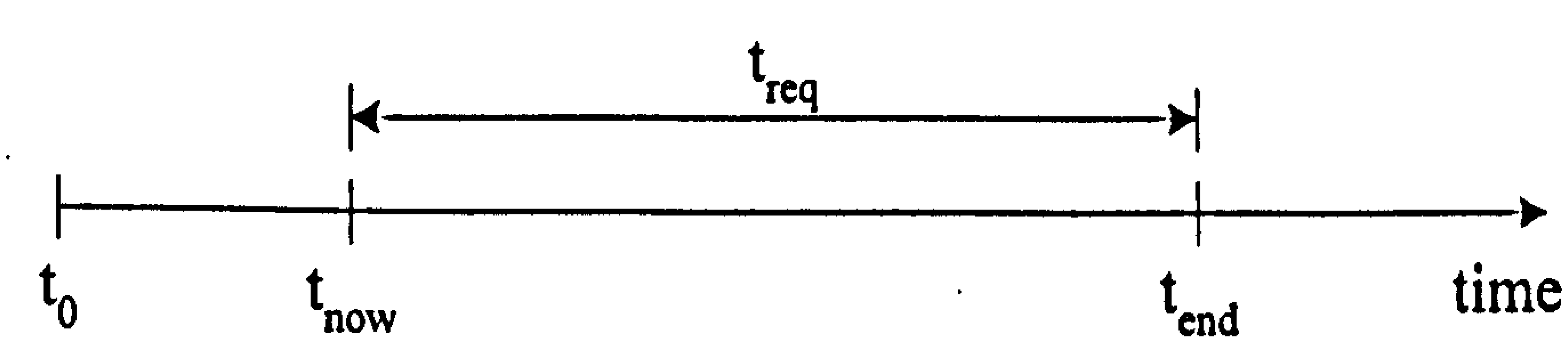


Figure 6.4 Time horizon and reference times

(4) Discount rate

Discount rates which are used to convert future costs into their present values at a given base year can be defined by specifying one or several pairs of time and discount rate data. In the program, the i_{th} discount rate, i.e. discount(i), is applied from corresponding year, i.e. year(i), until new discount rate, i.e. discount(i+1), is defined in year(i+1).

6.2.2 Maintenance options

In this data block, the number of maintenance options considered in the analysis as well as the maintenance plan generation method between an effective life concept or a performance index approach is specified. According to the method selected, additional data for specifying the characteristics of maintenance options are defined. In other words, either the effective lives of maintenance options or the effects of maintenance options on the performance profile of bridge structure are defined according to the method selected. Then all feasible maintenance plans can be generated based on these data, coupled with additional data needed for determining initial maintenance timing. In the following, the methodologies adopted in this study for generating maintenance plans based on an effective life concept and a performance index approach are explained in more detail.

6.2.2.1 Maintenance plan generation based on an effective life concept

According to the original effective life concept [64], the application timing of first maintenance option is determined by the maintenance free life of the applied option. However, this idea is applicable only to a newly constructed bridge structure which may adopt various durability options. This study which concentrates on the management of an existing bridge structure assumes that, instead of durability options, one maintenance option may or may not be applied at time t_0. Based on this assumption, the application timing of the first maintenance option is calculated by the following relations:

(1) If no maintenance option is applied at t_0, first maintenance option is applied at the present year (= t_{now}).

(2) If a maintenance option is applied at t_0, first maintenance option is applied at future time between t_{now} and $t_0 + T_{eff}$ where T_{eff} is the effective life of the maintenance. This allows the ability to use up the remaining life of previously applied maintenance options and to decrease the need of additional maintenance

activities.

After the application timing of the first maintenance option is determined, all the feasible maintenance plans are generated. Figure 6.4 presents a tree structure which shows how the maintenance plans are generated.

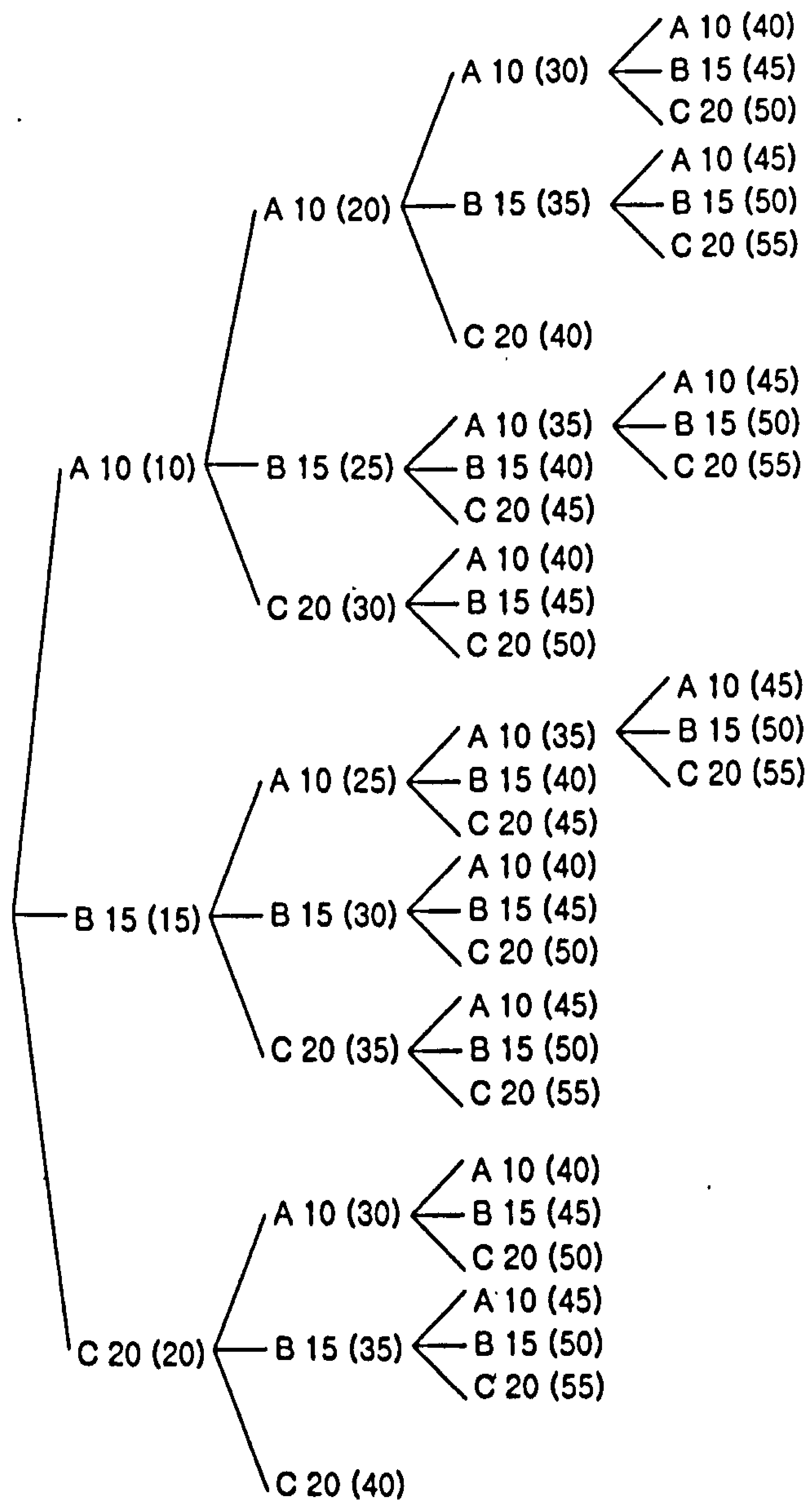


Figure 6.5 Tree structure showing the maintenance plan generation method.

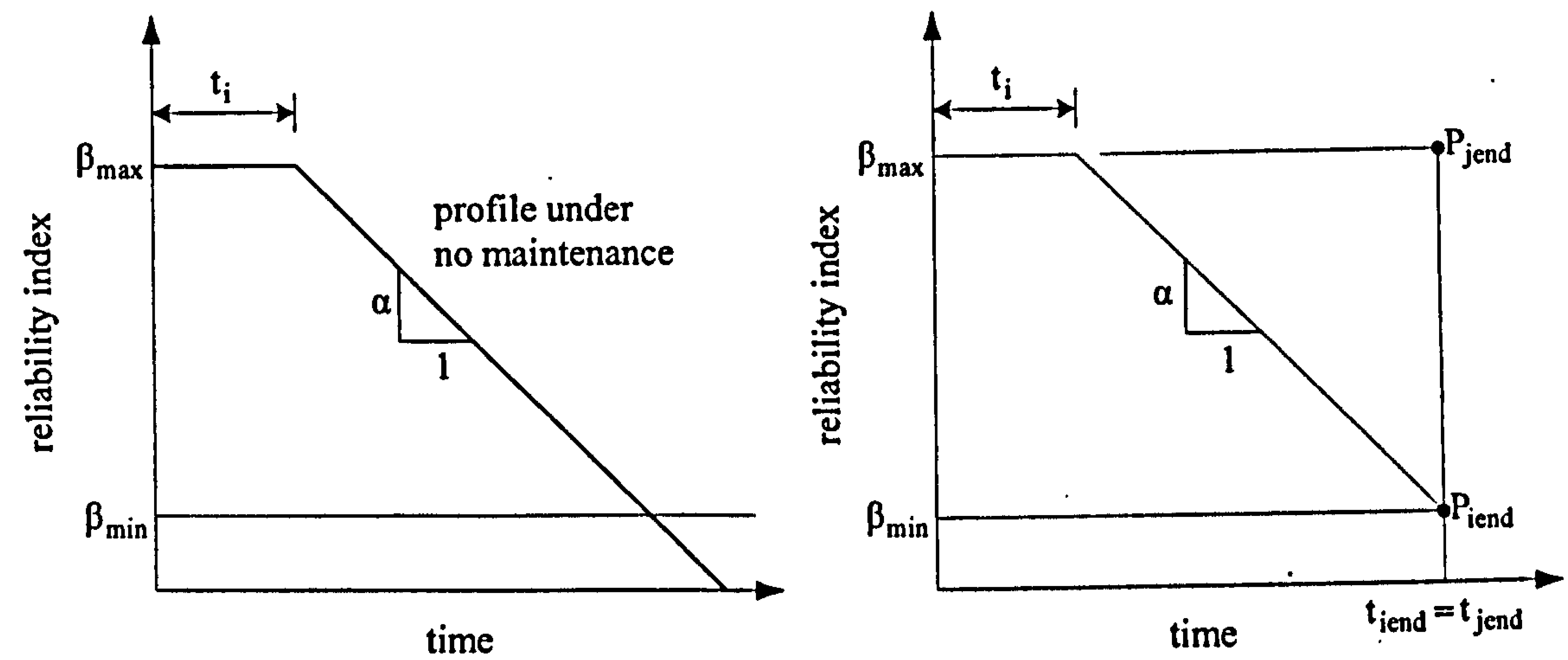
Here, it is assumed that three maintenance options A, B, and C have 10, 15 and 20 years of effective life, respectively, and that the maintenance horizon is 40 years. Thirty three maintenance plans such as 'AAAA', 'BAAA', 'CAA' and 'CC', etc. are generated. The number in the parenthesis represents the cumulative effective life of the chosen maintenance history. In case of the 'AAAA' maintenance plan, if the application timing of first maintenance option is 2000, 'A' maintenance option will be applied in 2000, 2010, 2020, and 2030, respectively. Based on the same principle, the order and application timing of all options in each plan are determined.

6.2.2.2 Maintenance plan generation based on performance index approach

Generation of maintenance plans based on a performance index approach is complex and the methodology is still developing. This study makes some changes in the existing methodology [121-128] in order to generate all feasible maintenance plans. More specifically, this study considers a single essential maintenance option (rebuild), multiple preventative maintenance options, and do nothing option as selectable maintenance options. Generation of maintenance plans is undertaken by combining these options until the cumulative maintenance lives are over the time considered as the maintenance horizon under the condition that the time-varying performance index is greater than or equal to a target index. The basic assumptions in applying these different types of maintenance options and corresponding changes in performance index profile are explained in more detail below. The definition of input variables used in the following can be found in Appendix C. For the purpose of explaining the approach the performance index is here assumed to be a reliability index, i.e. an index related to the notional safety of the bridge. However, any other performance index (e.g. live load capacity, live to dead load capacity, etc) could equally be introduced.

1) Essential maintenance option (rebuild)

Essential maintenance option is applied when the β value reaches β_{min}. In this case, it is assumed that the β value changes from β_{min} to β_{max} immediately as shown in Figure 6.6 (b).



(a) profile under no maintenance (b) profile under rebuild

Figure 6.6 Reliability index profile under no maintenance and rebuild.

Then the changes in reliability index and time can be expressed by:

$\beta_{iend} = \beta_{min}$

$\beta_{jend} = \beta_{max}$

t_{iend} = time when reliability index reaches β_{min}

$t_{jend} = t_{iend}$.

2) Do nothing option

If the number of available preventative maintenance options is n_{pm}, then $(n_{pm}+1)$ number of maintenance options including do nothing option can be applied at any one point above the minimum/target level. When 'do nothing option' is chosen, no maintenance option is applied until the reliability index reaches β_{min}.

Based on Figure 6.7, the changes in reliability index and time between P_{iend} and P_{jend} when 'do nothing' option is applied can be calculated by the following relationships:

In case of $\beta_{iend} < \beta_{max}$

$$\beta_{jend} = \beta_{min}$$

$$t_{jend} = t_{iend} + (\beta_{iend} - \beta_{min})/\alpha$$

In case of $\beta_{iend} = \beta_{max}$

$$\beta_{jend} = \beta_{min}$$

$$t_{jend} = t_{iend} + t_i + (\beta_{max} - \beta_{min})/\alpha$$

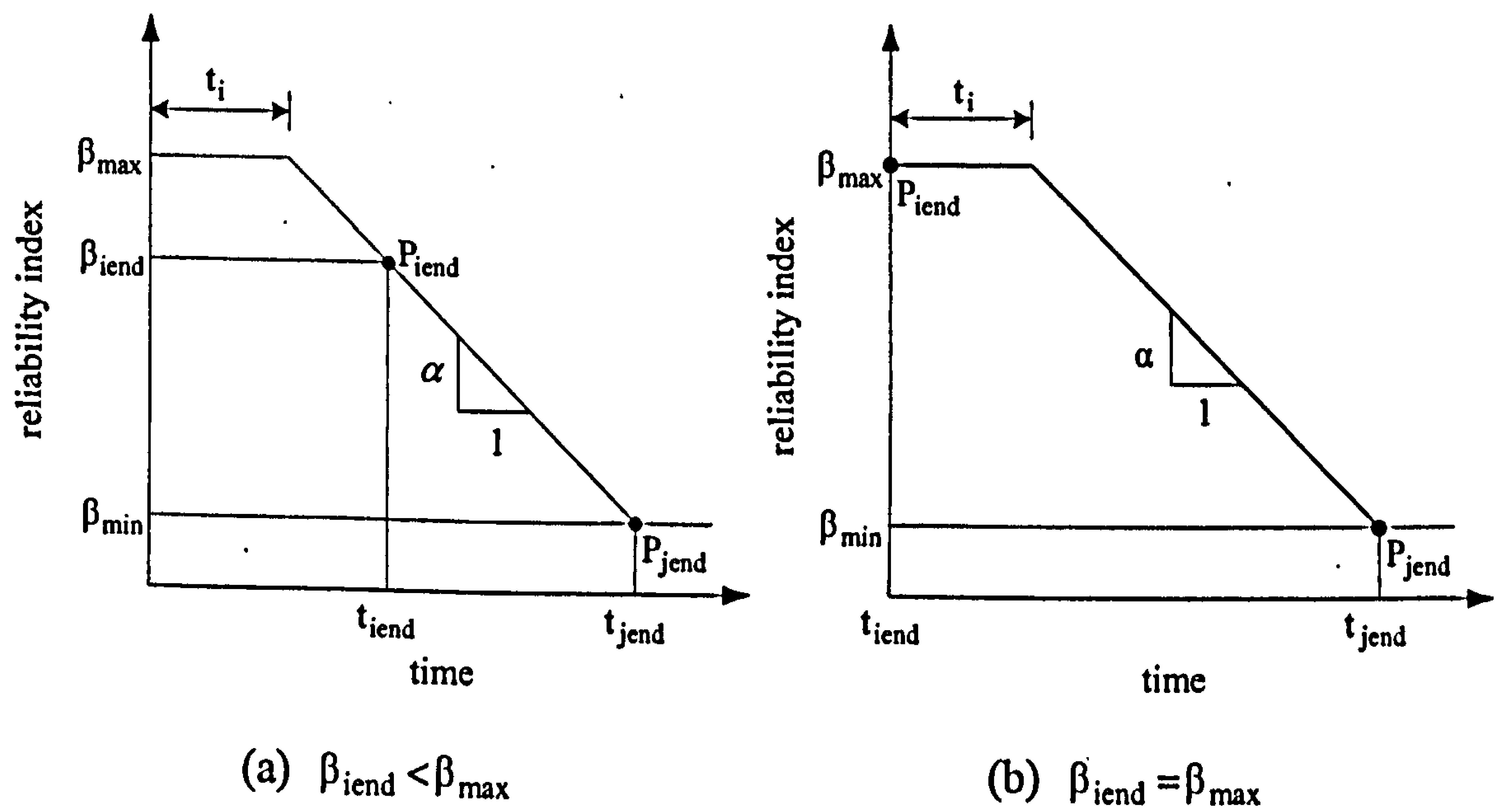


Figure 6.7 Reliability index profile under do nothing option.

3) Preventative maintenance options

Figure 6.8 shows the change of reliability index profile when a preventative maintenance option is applied. It is assumed that if the present time is less than t_{pi} (initial time to apply preventative maintenance), the application of preventative maintenance options is delayed until t_{pi}.

The changes of reliability index and time between P_{iend} and P_{jend} are:

In case of (a) $\beta_{jend} > \beta_{min}$

if $\beta_{iend} > \beta_{pi}$, then the application of preventative maintenance option is delayed until

$$\beta_{iend} = \beta_{pi},\ t_{iend} = t_{pi}.$$

if $\beta_{iend} < \beta_{pi}$, then preventative maintenance option is applied without delay.

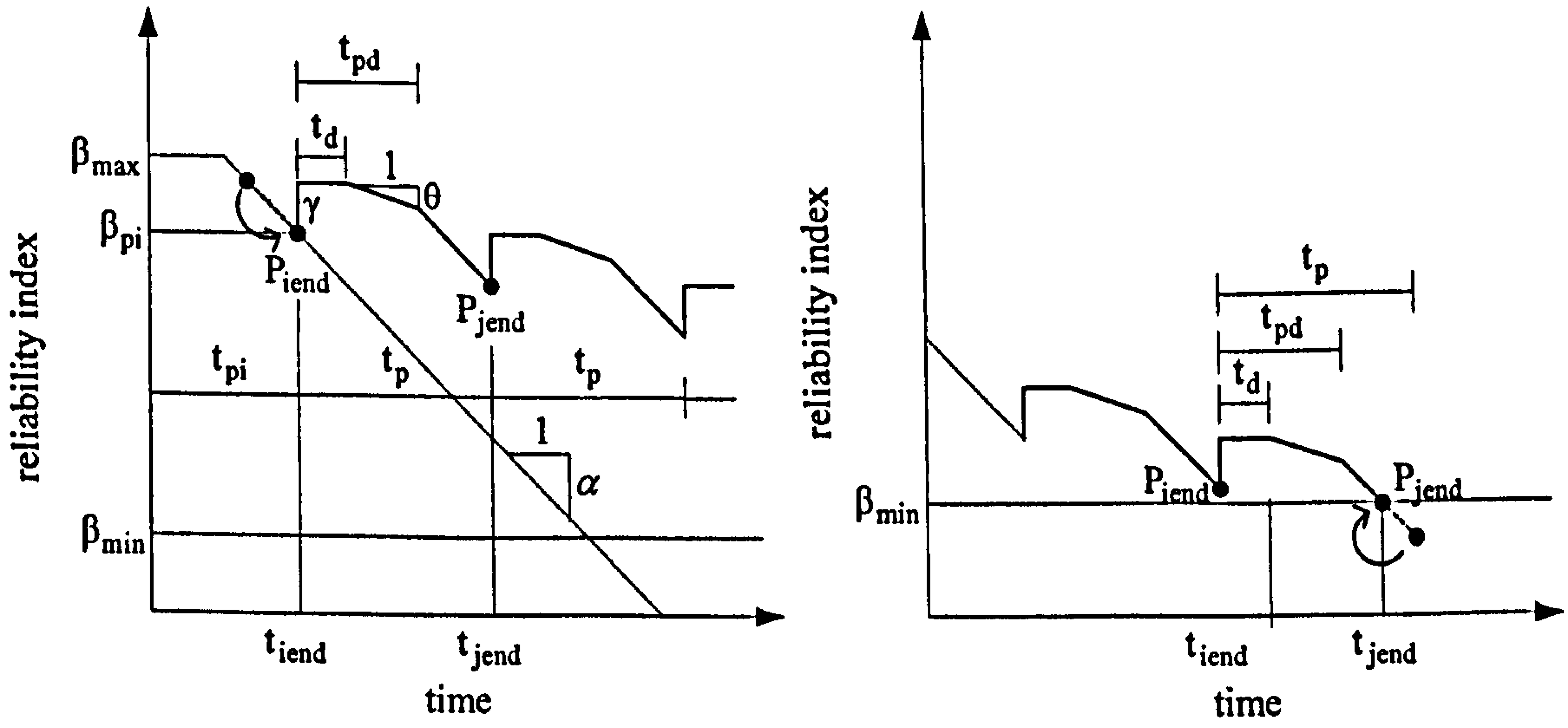
$$\beta_{jend} = \beta_{iend} + \gamma - (t_{pd} - t_d) \times \theta - (t_p - t_{pd}) \times \alpha$$

$$t_{jend} = t_{iend} + t_p$$

In case of (b) $\beta_{jend} < \beta_{min}$

if $\beta_{jend} < \beta_{min}$, then essential maintenance is applied when β reaches β_{min}.

Furthermore, t_{jend} can be easily found by calculating the time when the multi-linear reliability index profile related to preventative maintenance option reaches β_{min}.

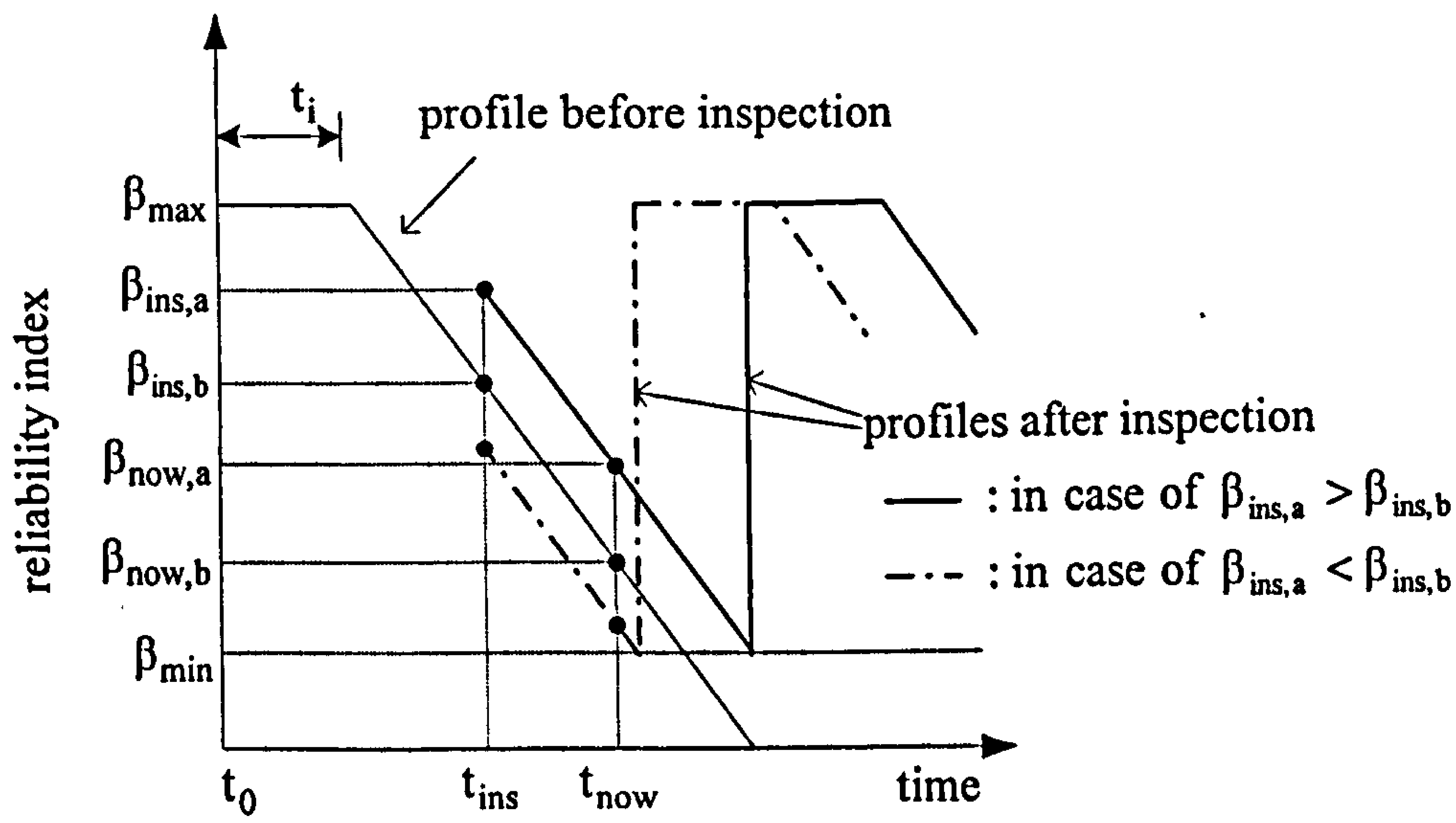


(a) $\beta_{jend} > \beta_{min}$ (b) $\beta_{jend} < \beta_{min}$

Figure 6.8 Reliability index profile under preventative maintenance.

4) Updating the performance profile using inspection data

If an inspection is undertaken between t_0 and t_{now} and the reliability index of bridge structure is calculated based on the inspection result, the program developed adjusts the theoretical reliability index profile by adjusting the initial value and hence shifting the profile horizontally as shown in Figure 6.9.



where, t_{ins} : time of inspection, t_{now} : time of the present year

$\beta_{ins,b}$: reliability index in the inspection year before inspection

$\beta_{ins,a}$: reliability index in the inspection year after inspection

$\beta_{now,b}$: reliability index in the present year before inspection

$\beta_{now,a}$: reliability index in the present year after inspection

Figure 6.9 Adjustment of reliability index profile when inspection data is available

6.2.3 Direct impact

Direct costs of maintenance options are inputted in cost per unit area (GBP/m^2). For this, direct costs arising from different sources such as purchase of material, workforce, use of machinery and traffic management should be calculated and summed up beforehand.

In a similar way, direct environmental scores of maintenance options are inputted in value per unit area (point/m^2). For this, it is assumed that a single environmental score representing all the environmental impacts related to a maintenance option can be obtained based on a selected LCIA methodology.

6.2.4 Indirect impact

6.2.4.1 The assignment of traffic management methods to maintenance options

In this study, the input data for calculating indirect impacts consist of two groups. They are:

1) Data for defining necessary traffic management schemes
2) Data for assigning traffic management schemes defined to maintenance options.

This approach has been introduced in order to effectively model the traffic management schemes of all maintenance options. If the same traffic management scheme is used for different maintenance options, the modelling of the traffic management scheme is required only once. In summary, the definition of traffic management situations related to maintenance options can be done by defining all the traffic management schemes representing different traffic management situations and assigning their indexes to bridge maintenance options.

When assigning traffic management schemes to maintenance options, the following three different cases may happen according to the site situation and the characteristics of maintenance option considered. They are:

1) No traffic management is required.
2) Traffic management is required either on or under the bridge.
3) Traffic management is required both on and under the bridge.

For modelling above three cases, in the developed program zero (T=0), one (T=tm1) or two (T=tm1, tm2) number of traffic management schemes can be assigned to one maintenance option and the corresponding indirect impacts are calculated and combined. For example, if two traffic management schemes are specified to one maintenance option, the program calculates indirect costs and environmental scores twice for two traffic management schemes and sums them up.

The time basis for traffic modelling in the program is one week. It means that the indirect costs and environmental scores related to maintenance options should be multiplied with the works durations (the number of weeks required to finish each maintenance option). Therefore, when the traffic management schemes related to maintenance options are specified in the input file, the data regarding works durations of maintenance options also need to be given.

In the next section, the data requirements for defining traffic management scheme are explained in more detail.

6.2.4.2 The data requirements for defining traffic management scheme

The QUADRO program requires a number of input data. The unit of data input in the QUADRO program is KEY, and each KEY consists of a set of relevant data. According to the QUADRO manual, 40 KEYs and 20 KEYs are necessary for inputting Basic data and Job data, respectively. Among them, some KEYs are mandatory and other KEYs are used to change the default values. The default values have been determined based on the nationally collected statistical data, and if local data is not available, the default values could be used. In this study, the default values are used as much as possible in order to minimise the input data requirements. The types of input data required in the program developed in this study for defining traffic management scheme are summarised below. In addition, their usage and selectable options are explained in more detail.

<u>Input data associated with main route</u>

(1) Network classification
(2) Road class
(3) Accident type in main route
(4) Dimension of main route
(5) Works type
(6) Tidality factor
(7) Traffic flow in main route

<u>Input data associated with diversion route</u>

(8) Dimension of diversion route
(9) Accident type in diversion route

(10) Traffic flow in diversion route

(11) Speed/flow relationships in diversion route

Input data associated with environmental score of fuel consumption

(12) Unit environmental scores related to fuel consumption

(1) Network classification

The road network type is selected from (1) motorway, (2) non built-up trunk, (3) non built-up principal, (4) build-up trunk, and (5) built-up principal. If the network type is specified, the corresponding default values of seasonality index (SI) and vehicle category proportions are determined. These values are, in turn, used to describe annual traffic flow pattern in the specified road network.

(2) Road class

In the QUADRO program, road class of the route concerned is classified into eleven types according to the location (rural, motorway, urban, small town and suburban) and the number of lanes (single, dual 2, dual 3, dual 4 or more lanes). However, in this study only former six road classes corresponding to rural road and motorway are considered as already explained in the section 4.4. According to the type of road class specified, the parameters associated with the speed/flow relationships in the absence and presence of site works are defined, hence road class affects the calculation of time delay due to road works.

(3) Accident type in the main route

The accident type in the main route in the absence of site works should be specified. Then the accident type in the presence of site works is automatically determined. These two values, in turn, determine the corresponding accident rates and accident costs data. The net accident costs in the main route are calculated based on these data coupled with the results of General Delay Sub-model.

(4) Dimension of main route

As part of road network system, the length of main route, site length and approach length need to be specified. The schematic diagram of the network system is shown Figure 4.2.

(5) Works type

The works type specified defines traffic management layouts such as the number of open lanes in the direction considered and, if any, contra-flow working. The type of road class explained in above (2) and works type together determine the journey time relationship in the presence of site works. For reference, the journey time relationship in works site is presented below and the variation of K, K_1, K_2 and K_3 can be found in the Table 1/3, Part 5 of QUADRO manual [141].

$$JT=K+K_1*Bendiness+K_2*Hilliness/2+K_3*Flow \qquad (6.4)$$

where, JT = journey time in minute per km,

Bendiness is measured in deg/km,

Hilliness is measured in m/km,

Flow is vehicle/hr/standard (3.65m) lane,

K, K_1, K_2 and K_3 are constants dependent on road class, works type and flow.

(6) Tidality factor

In the QUADRO program, the total flows of both directions are split into flows of primary direction and secondary direction. The splitting proportions of traffic flows vary according to the location of works site and hour of a day. Tidality factors are used to take account of this variation and their values are determined according to two options 'A' and 'B'. Table 6.2 presents the tidality factors associated with option 'A' where primary direction is carrying more traffic in Monday am peak. Secondary direction tidality factors can be calculated by subtracting them from unity. On the other hand, the tidality factors of option 'B' can be calculated by subtracting the tidality factors of option 'A' from unity.

Table 6.2 Primary direction tidality factors for all network classifications ([141])

Hour of Day	Mon-Fri	Sat	Sun
1-8	0.5	0.5	0.5
9	0.57	0.5	0.5
10-12	0.5	0.5	0.5
13	0.5	0.43	0.5
14-17	0.5	0.5	0.5
18	0.43	0.5	0.57
19-24	0.5	0.5	0.5

The tidality factors in the primary and secondary direction of diversion route are assumed to be same with those of main route.

(7) Traffic flow on the main route

It is required to determine the level of flow on the main route for each job. The QUADRO program provides four methods of doing this:

(1) Annual Average Hourly Traffic (AAHT) in a given year

(2) A single 12-hour traffic flow (0700 -1900) for a given year and month

(3) A single 16-hour traffic flow (0600-2200) for a given year and month

(4) Annual Average Daily Traffic (AADT) in a given year.

In this study, AADT value is adopted to specify the level of traffic flow in the reference year (or traffic observation year). Then traffic flow in the repair year is calculated considering national average road traffic forecasts. The traffic flow in the repair year is split into 24 hours traffic profiles of one week step by step. The overall framework of traffic splitting is shown in Figure 6.10. The specific data used in each step are not described here, but they can be found in QUADRO manual [141].

(8-10)Dimension, accident type and traffic flow of diversion route

Based on the same principles and methods used in the main route, the lengths in two directions, accident type and traffic flow of diversion route need to be specified.

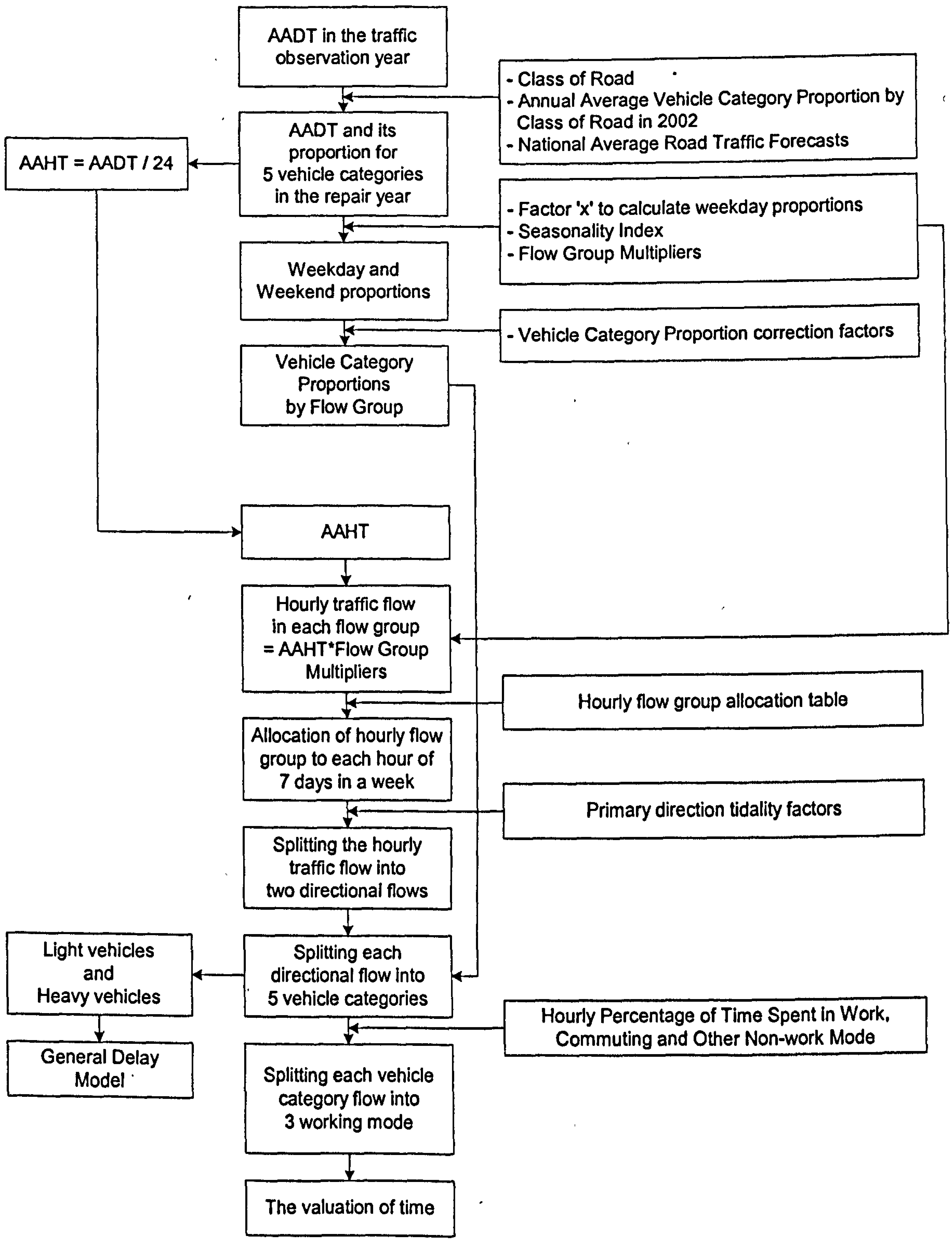


Figure 6.10 Procedure of traffic flow splitting and its usage

(11) Speed/flow relationship on the diversion route

For calculating the time delay on the diversion route, the analyst should define the speed/flow relationship on the diversion route. In the QUADRO program, the speed/flow relationship on the diversion route is defined by a free speed (V_0) and up to five flow/speed pairs. The points are specified as 'break points' between linear speed/flow slopes, and the final speed specified is taken as minimum speed (V_{min}). Figure 6.11 illustrates the simplest and most complex relationship possible. In this study, the same methodology is applied to define the speed/flow relationship on the diversion route. However, the program developed has no limitation in the number of additional flow/speed pairs.

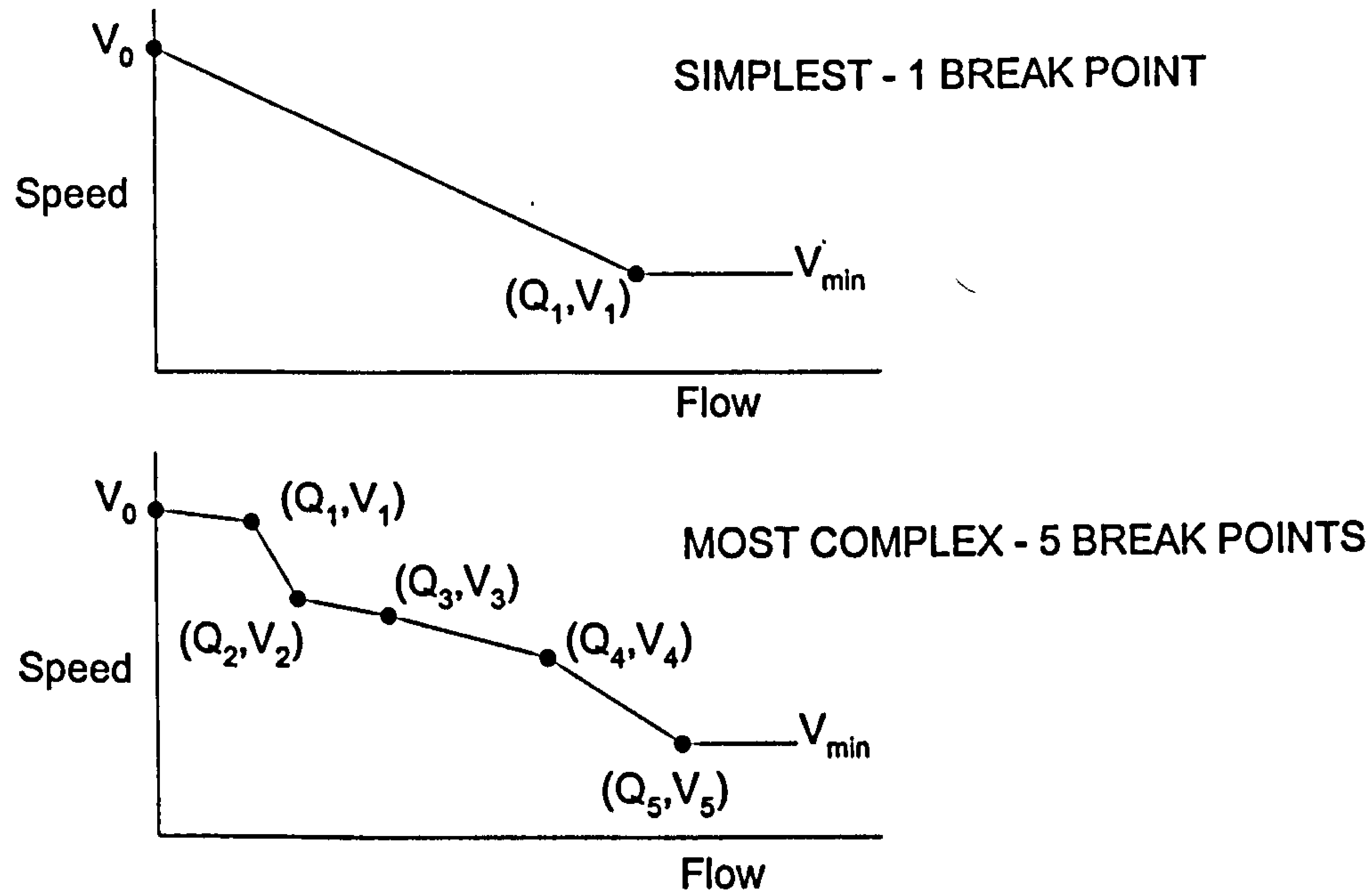


Figure 6.11 Possible forms of speed/flow relationship in the QUADRO ([141])

(12) Environmental score related to fuel consumption

The program developed calculates the amounts of additional fuel consumption (in litres) for a given traffic management situation, and then converts them into environmental scores. The environmental scores related to 1 litre petrol and diesel production are used for this conversion.

6.2.5 Weighting factors

As already explained in the section 6.1.2, two kinds of weighting factors are taken into account in order to reflect the decision maker's preferences. These are (1) weighting factors for direct and indirect impacts; (2) weighting factors for cost and environmental score.

Firstly, the weighting factors for direct and indirect impacts are introduced. The program developed calculates total costs and environmental scores of maintenance plans by combining direct and indirect impacts arbitrarily using the linear relationships shown below.

$$C_{Ti} = C_{Di} \times w_{DC} + C_{Ii} \times w_{IC} \tag{6.5}$$

$$E_{Ti} = E_{Di} \times w_{DE} + E_{Ii} \times w_{IE} \tag{6.6}$$

where, C_{Ti} : total cost of i_{th} maintenance plan.

E_{Ti} : total environmental score of i_{th} maintenance plan.

C_{Di}, C_{Ii} : direct and indirect cost of i_{th} maintenance plan, respectively.

E_{Di}, E_{Ii} : direct and indirect environmental score of i_{th} maintenance plan, respectively.

w_{DC}, w_{IC} : weighting factors for direct and indirect cost, respectively.

w_{DE}, w_{IE} : weighting factors for direct and indirect environmental score, respectively.

Secondly, weighting factors for cost and environmental score are introduced to calculate an overall preference of optimal maintenance plans. As can be seen in formula (2.3) in the section 2.2.6, they are multiplied with the normalised total cost and total environmental score and produce overall weighted score for maintenance plans. In this study, only weighting factors for cost are inputted and weighting factors for environmental score are automatically calculated by subtracting weighting factors for cost from unity. Based on the specified weighting factors for cost and environmental score, the developed program traces the variation of an 'optimal' maintenance plan as well as counts their frequency.

6.3 Conclusions

In this chapter, a quantitative methodology in which an optimal bridge maintenance plan is determined by combining economical and environmental indicators has been developed. For this, several methods related to generating maintenance plans, calculating indirect impacts due to traffic disruption, combining direct and indirect impacts using weighting factors and integrating costs and environmental scores with MCDA techniques have been developed and appropriately integrated. Furthermore, the methodology has been developed on not only deterministic but also probabilistic basis and hence some additional methods associated with generating random variables, checking convergence in the probabilistic analysis results and counting the frequency of optimal maintenance plans have also been suggested.

More specifically, main functions of the methodology and their embodiment in the program have been explained in the sections 6.1 and 6.2, respectively. Furthermore, the whole structure of input file and the specific meaning of input data are presented in Appendix C. Finally, the structure of output file is not described here, but they will be shown with some case studies in Chapter 7.

Chapter 7

Case studies

7.1 Introduction

In order to demonstrate the validity of the proposed methodology in finding preferable bridge maintenance options/practices in terms of sustainability, a number of case studies are executed based on the following sequence.

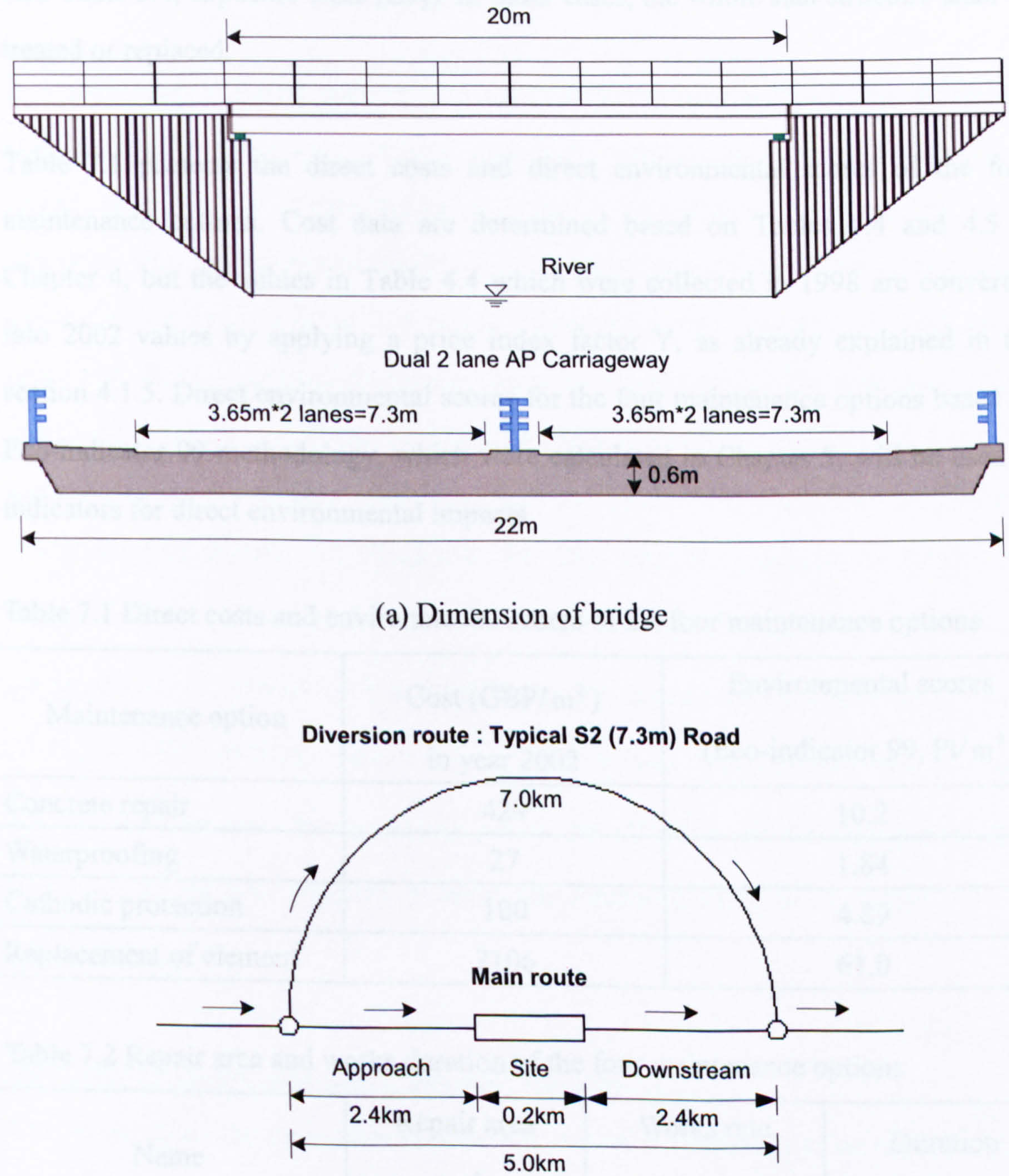
1) Description of an example
2) Deterministic analysis
3) Probabilistic analysis

7.2 Description of an example

The example chosen in this study is the maintenance of a slab structure of a single span simply supported reinforced concrete bridge on the non built-up trunk road network. In the following the basic assumptions associated with (1) bridge dimensions and maintenance requirement, (2) maintenance options considered and their characteristics and (3) traffic conditions and traffic management scheme are explained.

(1) Bridge dimensions and maintenance requirement

The dimensions of the bridge structure and the characteristics of the assumed road network system are illustrated in Figure 7.1. This is a typical slab-type structure found on the trunk road network. Many of these structures were constructed in the late 1960s and early 1970s, and have, to a varying degree, exhibited durability problems. Unless otherwise stated, it is assumed that this slab structure has been rehabilitated in 2002 and should be maintained for further 60 years. The reference year for discount is 2002: a 3.5% of discount rate is applied until 2032 and a 3% of discount rate is applied from 2033 onwards. For simplicity, the present year is also assumed to be 2002.



(a) Dimension of bridge

(b) Road network system

Figure 7.1 Bridge dimension and road network system

(2) Maintenance options considered and their characteristics

Concrete repair (CR), waterproofing (WP), cathodic protection (CP) and replacement of element (RE) are selected as four alternative maintenance options for the slab structure. Among them, replacement of element option is regarded as an essential maintenance action, while the others are considered as preventative actions. In the case of the concrete repair option, it is assumed that 10 % of the slab area is repaired (see Table 3.4, exposure class [E3]). In other cases, the whole slab structure shall be treated or replaced.

Table 7.1 presents the direct costs and direct environmental scores of the four maintenance options. Cost data are determined based on Tables 4.4 and 4.5 in Chapter 4, but the values in Table 4.4 which were collected in 1998 are converted into 2002 values by applying a price index factor Y, as already explained in the section 4.1.5. Direct environmental scores for the four maintenance options based on Eco-indicator 99 methodology, which were calculated in Chapter 5, will be used as indicators for direct environmental impacts.

Table 7.1 Direct costs and environmental scores of the four maintenance options

Maintenance option	Cost (GBP/m^2) in year 2002	Environmental scores (Eco-indicator 99, Pt/m^2)
Concrete repair	429	10.2
Waterproofing	27	1.84
Cathodic protection	100	4.89
Replacement of element	2106	61.0

Table 7.2 Repair area and works duration of the four maintenance options

Name	Repair area (m^2)	Works rate (m^2/week)	Duration (weeks)
Concrete repair	44 (10%)	8	5.5
Waterproofing	440	100	4.4
Cathodic protection	440	50	8.8
Replacement of element	440	8	55

The repair area and works duration of the four maintenance options are given in Table 7.2, and are based on [75]. As shown in Table 3.4, the works rate for concrete repair is 2~8 m^2/week. If the rate of 2 m^2/week is selected, it would take 220 weeks to execute 'replacement of element' option. This is considered unrealistic, so in this study a works rate of 8 m^2/week is used for concrete repair and replacement of element.

If a performance based approach is used in developing maintenance plans, the change in performance index profiles associated with maintenance options should be known. However, the availability of such data is quite limited at present. Therefore, this study uses the change in the live load capacity factor C related to maintenance options which were included in a recent Highways Agency report [129] and, where necessary, some additional reasonable assumptions are made. The definition of the live load capacity factor C can be found in clause 5.27 of BD 21/01 [194]. Table 7.3 summarises the parameters associated with the models for change in performance index whereas Figure 7.2 illustrates the four profiles graphically. Among the parameters, the value of the initial/maximum C factor (C_{max}) will be studied parametrically in section 7.3.3 in order to analyse the relationship between the value of C_{max} and the resulting characteristics of the optimal maintenance plans. In Figure 7.2, the time periods shown correspond to the effective life of each preventative action, or to the time required to reach the threshold value of C_{min}=0.91 for the essential action.

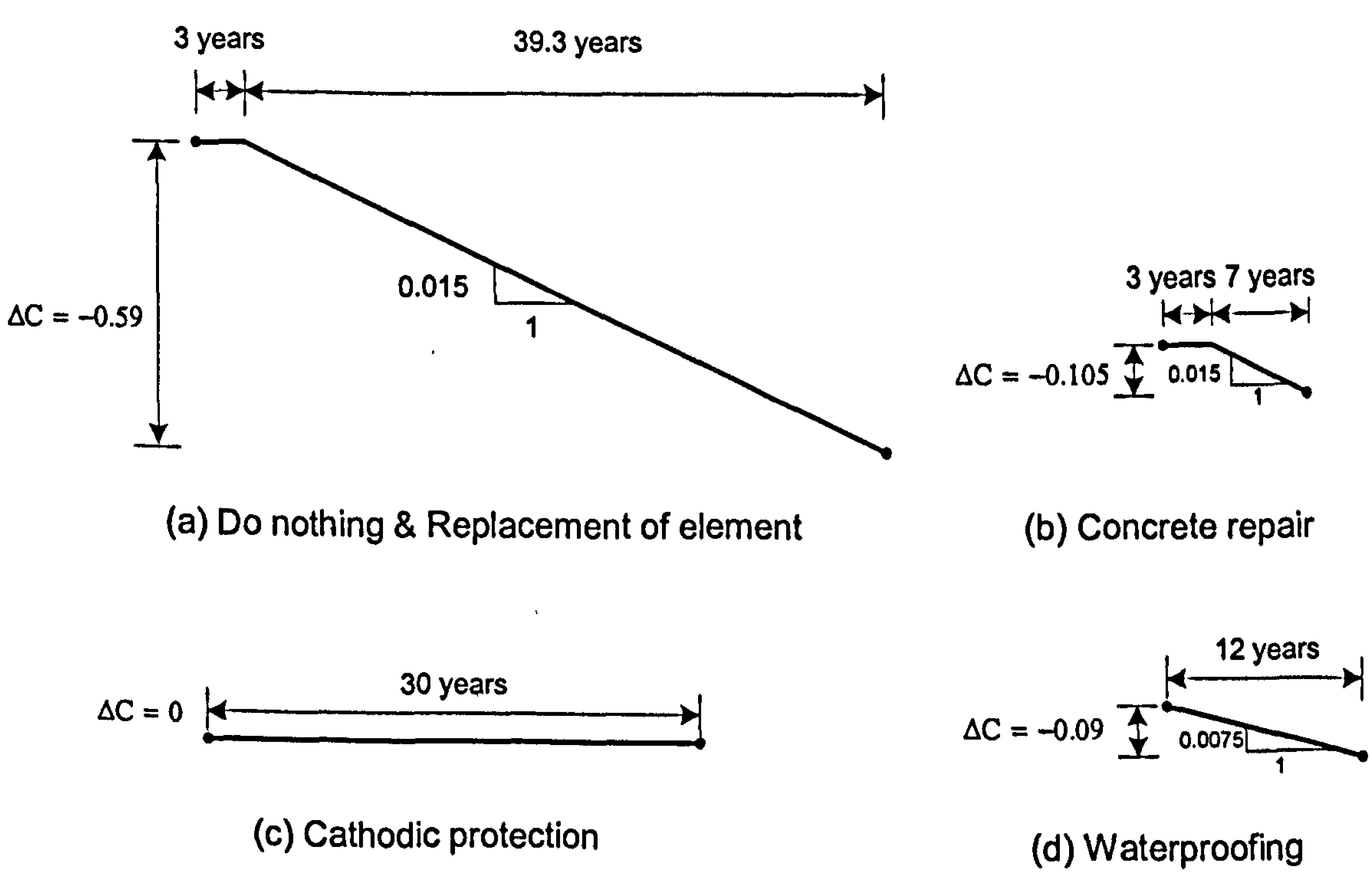
(3) Traffic conditions and traffic management scheme

The traffic flows on the main and diversion routes are assumed to be 60,000 AADT and 12,000 AADT in 2002, respectively. However, in section 7.3.4 the traffic flow on the main route will be studied parametrically in order to evaluate its impact on the indirect impacts and the resulting optimal maintenance plans. The speed-flow relationship of the diversion route is determined based on Figure 7.3.

Table 7.3 Change of performance index profile related to four maintenance options

Essential maintenance			
Profile index	Replacement of element		
C_{max}	1.5		
C_{min}	0.91		
t_i	3		
α	0.015		
Preventative maintenance			
Profile index	Concrete repair	Cathodic protection	Waterproofing
t_{pi}	10	0	0
t_p	10	30	12
t_{pd}	3	30	12
t_d	3	30	0
θ	0	0	0.0075
γ	0	0	0

Note: Above symbols are defined in the section 6.2.2 and Appendix C.2.



(a) Do nothing & Replacement of element
(b) Concrete repair
(c) Cathodic protection
(d) Waterproofing

Figure 7.2 Performance index profiles of four maintenance options

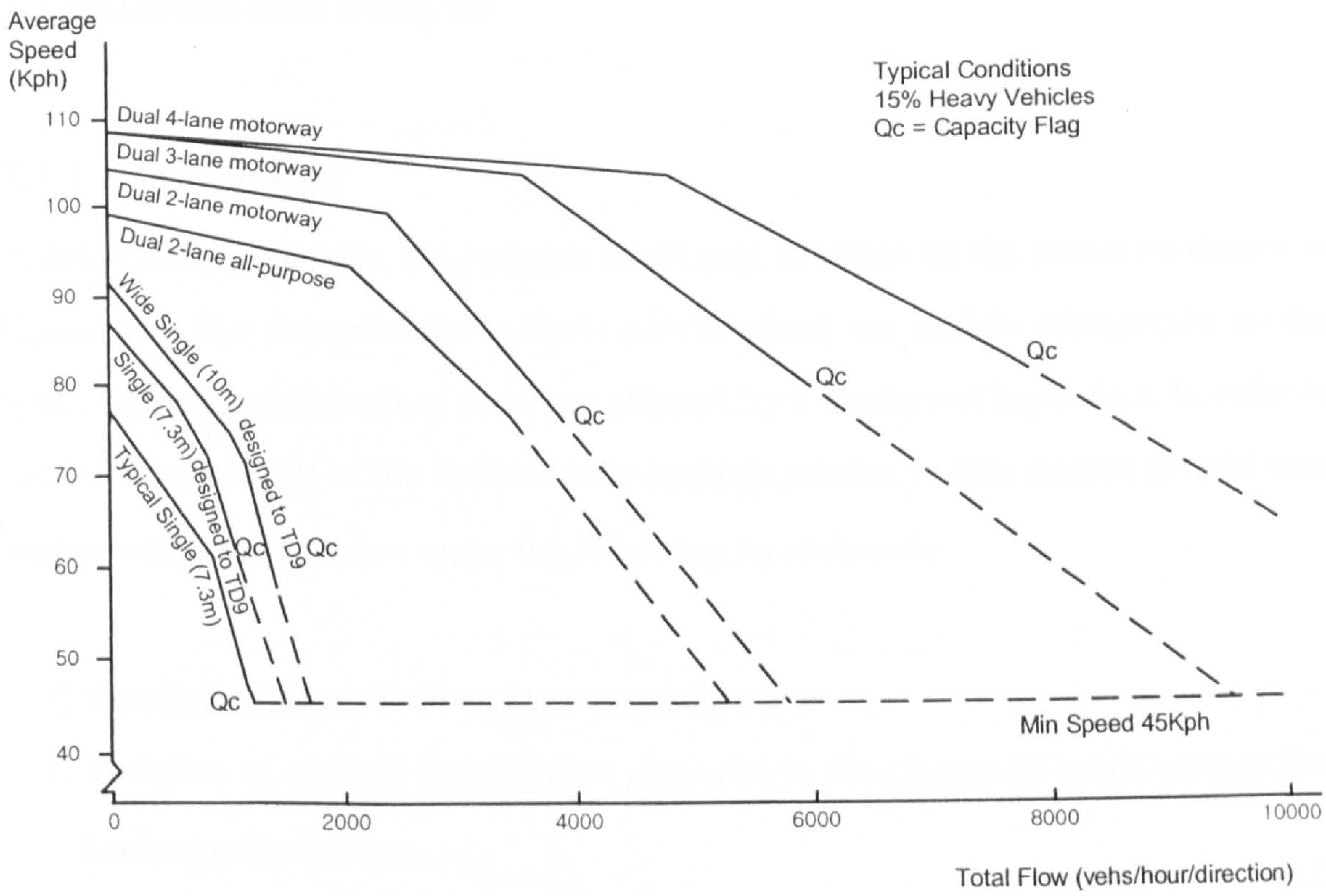


Figure 7.3 Typical rural speed/flow relationships ([142])

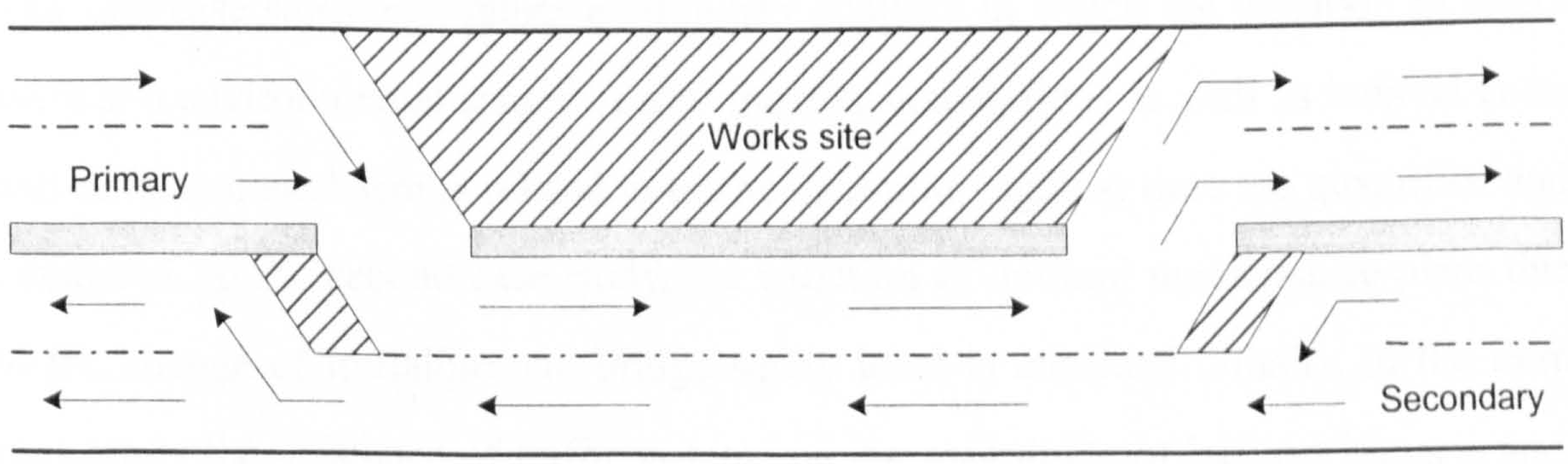


Figure 7.4 Traffic management scheme in works site

Figure 7.4 illustrates the assumed traffic management scheme during maintenance activities. In the primary direction, one lane is open in contra-flow (i.e. work type = 11) and one lane is open in the secondary direction (i.e. work type =1).

As unit indirect environmental scores for 1 litre consumption of petroleum and diesel, 0.129 and 0.144 will be used, respectively, based on Eco-indicator 99 methodology. (See the section 5.5.4)

7.3 Deterministic analysis

7.3.1 Introduction

In deterministic analysis, the program developed executes all the processes shown in Figure 6.1. The deterministic analysis results which are mainly represented by the type of optimal maintenance plans are affected by a number of input data. In order to show the variability of the deterministic analysis results, in this section several case studies will be undertaken under the following three themes.

1) Variation of direct/indirect impacts against time.
2) Variation of optimal maintenance plans due to the change of initial/present live load capacity factors.
3) Variation of optimal maintenance plans due to the change of traffic volume.

The first case study is a rather preliminary analysis in which the variation of direct costs and environmental scores of four maintenance options as well as indirect costs and environmental scores related to traffic disruption against time are quantified and compared. In the second case study, the variation of optimal maintenance plans due to the change of initial/present bridge safety level is analysed. Finally, in the third case study the influence of traffic volume on the magnitude of indirect impacts and, accordingly, on the type of optimal maintenance plans, is analysed.

For these case studies, the basic assumptions on input data highlighted previously are used. However, in the second and third case studies, the input data related to initial/present live load capacity factor and the amount of traffic volume will be changed, respectively, to analyse their effects.

7.3.2 Variation of direct/indirect impacts against time

Figure 7.5(a) presents the variation of direct costs (after discounting) against time for the four maintenance options considered. This figure simply shows the effect of discounting on net present value. Clearly, the cost reduces as the time of application of any maintenance action is delayed. On the other hand, Figure 7.5(b) presents the variation of direct environmental scores for the same four maintenance options with time. Since in this case no discounting is considered acceptable, as explained in section 6.1.2, the lines remain horizontal. It is evident from Figure 7.5(a) and (b) that option RE is associated with much larger direct costs and environmental scores than any other option.

Figure 7.5(c) shows the variation of indirect costs with time. The total indirect cost consists of delay time cost, vehicle operating cost (fuel and non-fuel elements) and accident cost. Among them, the proportion of delay time cost is 80~85% of the total indirect cost, whereas the others together correspond to 15~20%. Clearly, most of the indirect costs are related with delay time cost.

The net present values of total indirect costs due to road works undertaken in 2022, 2042 and 2062 are around 130%, 99% and 73% of the value in 2002, respectively. These percentages are much larger than the corresponding values of 50%, 26.5% and 15% for direct costs. The main reason for this is that according to current TRL assumptions as given in the QUADRO manual [141] the traffic is assumed to grow around 0.7~2.6% per annum from 2003 to 2031 but zero growth is assumed post 2031. Furthermore, unit costs related to user delay, fuel consumption and accident are also assumed to increase with time. Therefore, indirect costs have a different pattern compared to direct costs. The net present value of indirect costs increases with time for as long as the positive traffic growth is assumed.

Figure 7.5(d) presents the variation of indirect environmental scores related to road works undertaken in 2002, 2022, 2042 and 2062. The two vehicle classes of 'Car' and 'OGV2' produce larger environmental scores than other vehicle classes. This result arises from the fact that the proportion of 'Car' category is around 75~85% of all vehicles [141] and fuel consumption per unit distance of OGV2 is larger than those of other vehicle classes (See Figure 5.19).

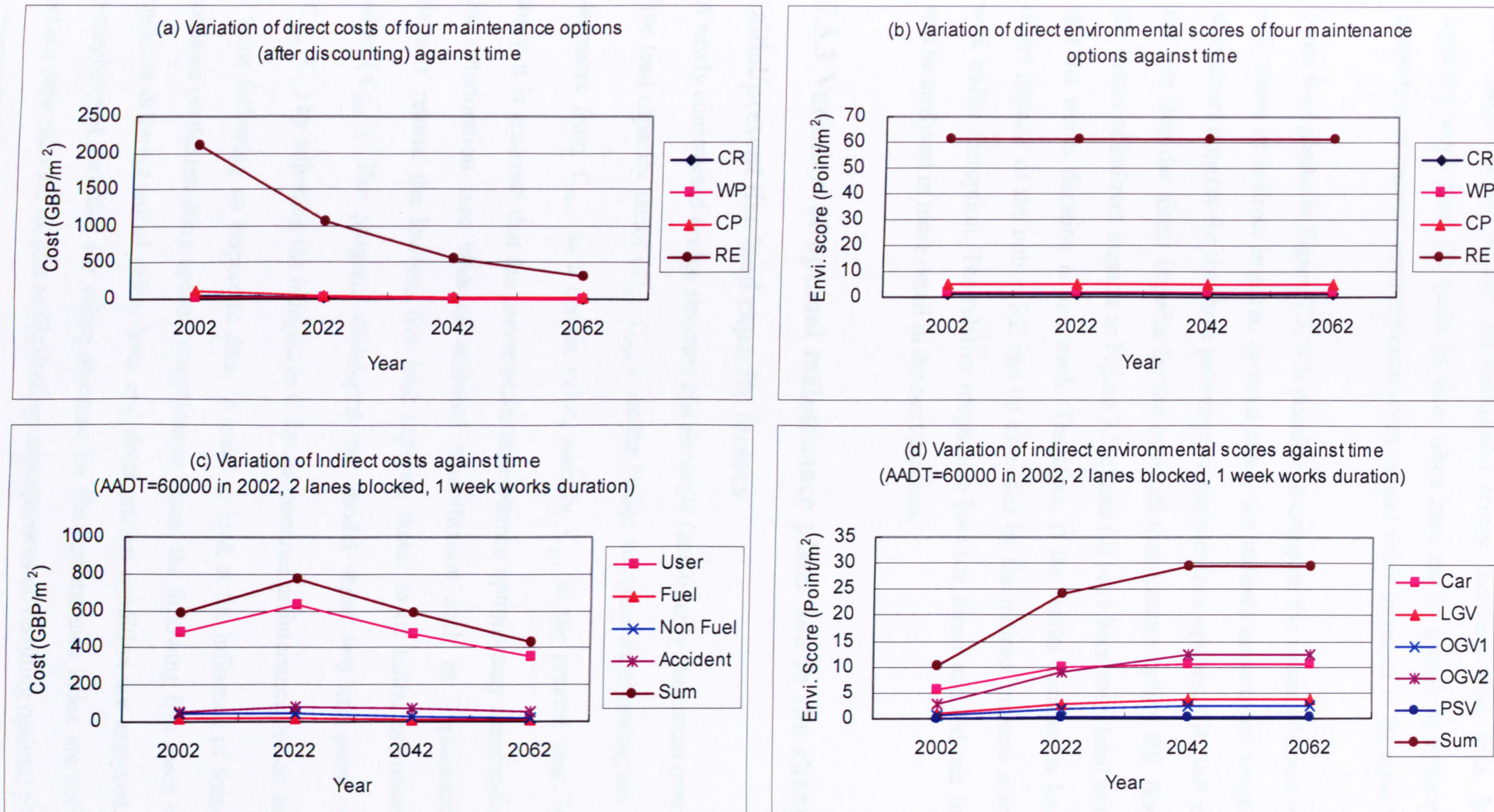


Figure 7.5 Variation of direct & indirect impacts against time

The magnitude of indirect environmental scores increases with time, but this tendency stops after the point in time when zero traffic growth is assumed. The proportion of indirect environmental score in total value increases in the same way.

From four graphs in Figure 7.5, it is possible to compare the values of direct impacts with those of indirect impacts. In most cases, the indirect impacts are much larger than direct impacts for the three preventative maintenance options, CR, WP and CP, but less than the direct impacts for the essential maintenance option RE. However, the values of indirect impacts in Figure 7.5(c) and (d) have been calculated assuming that the works duration is one week. Therefore, if the works duration is long, the direct impacts of the option RE can be exceeded by the indirect impacts associated with traffic disruption. The relative magnitude between direct and indirect impacts will be analysed in more detail in the next sections.

7.3.3 Variation of optimal maintenance plans due to the change of initial/present live load capacity factors

A newly constructed bridge structure has an initial (and usually maximum over time) live load capacity factor (C_0, C_{max}). As the bridge structure deteriorates, the factor decreases from C_{max} to a certain value, namely C_p, in the present year. In this study, it is assumed that the preventative maintenance options may suppress/reduce the deterioration rate whereas essential rehabilitation such as 'replacement of element' returns the lowered live load capacity factor to its initial as-constructed value (C_{max}). The program developed can model these two end-point values (C_{max}, C_p) by adjusting the increase in C for an essential maintenance option and the C value following an inspection data. In order to look at the influence of these two variables on the resulting optimal maintenance plans, the following five cases which represent different initial safety level and deterioration condition are analysed. It is re-emphasised here that the values assumed for the performance index are notional, and are only relevant insofar as illustrating consequences on resulting optimal plans.

(1) C_{max}=1.8, C_p=1.8 - high initial safety level and no deterioration

(2) C_{max}=1.5, C_p=1.5 - medium initial safety level and no deterioration

(3) C_{max}=1.5, C_p=1.3 - medium initial safety level and slight deterioration

(4) C_{max}=1.5, C_p=1.0 - medium initial safety level and severe deterioration

(5) C_{max}=1.3, C_p=1.3 - low initial safety level and no deterioration

The corresponding performance profiles for the above five cases are illustrated in Figure 7.6 when assuming that the bridge is managed by adopting 'do nothing' and 'replacement of element' options only.

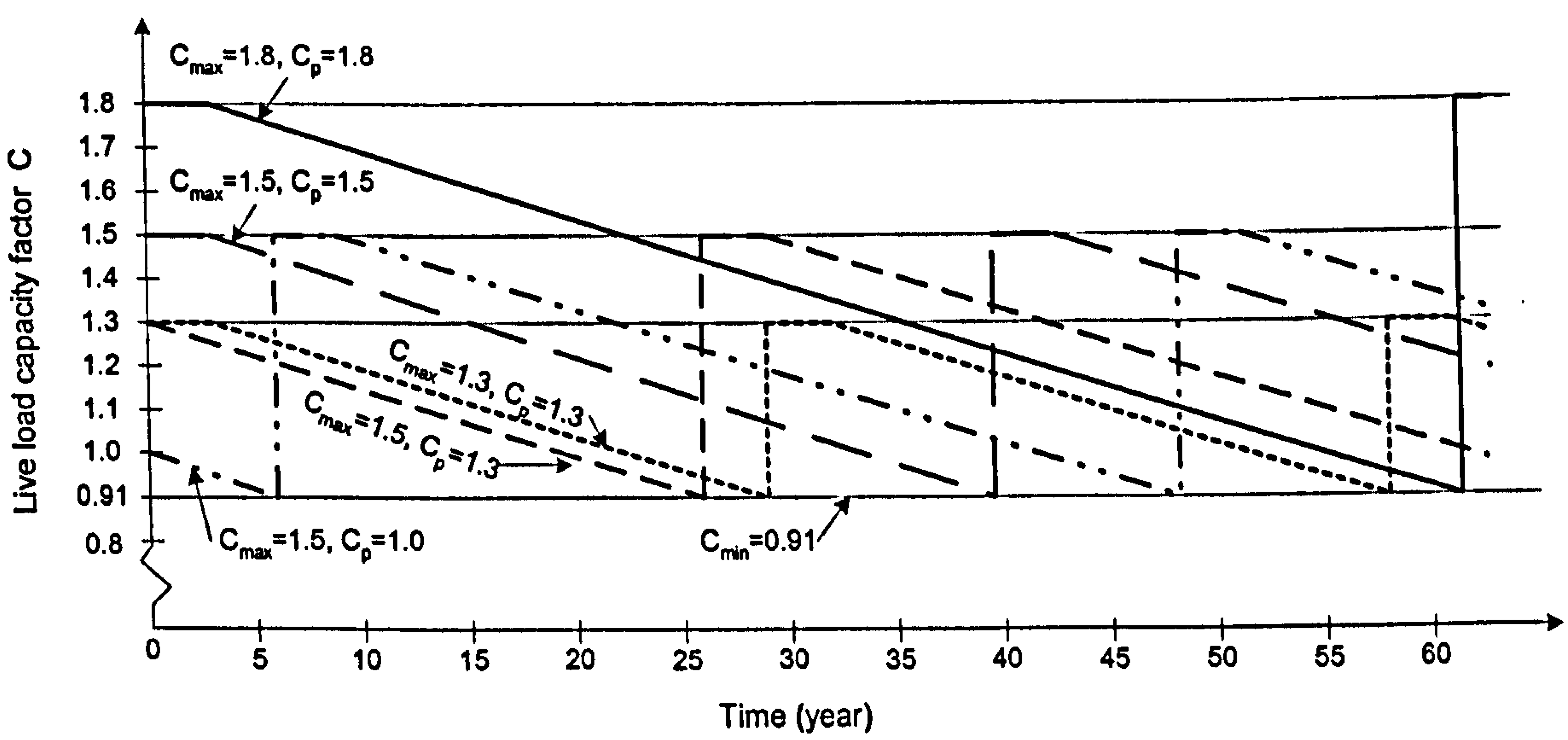


Figure 7.6 Variation of performance profiles according to C_{max} and C_p values

In Table 7.4, the optimal maintenance plans and their characteristics for the above five cases, considering direct impacts only, indirect impacts only and both impacts are summarised. The corresponding input files as well as the graphical distribution of cost and environmental score of the maintenance plans generated in each case are presented in Appendix D. Furthermore, as a way of verifying the credibility of the computer code developed in this study in generating a maintenance plan and calculating direct cost and environmental score, one of the optimal maintenance plans in case of C_{max}=1.5, C_p=1.5, i.e. (92) CR-WP-WP-CR-DN, is analysed by hand and compared with the results in Table 7.4. Their details are given in Appendix D.3. On the other hand, the validity of the computer code in calculating indirect cost was already discussed in the section 4.4 and Figure 4.10. Some conclusions which can be drawn from Table 7.4 are:

1) The type of optimal bridge maintenance plans varies according to the initial/present live load capacity factor of the bridge structure. For example, if the present live load capacity factor is high (C_{max}=1.8, C_p=1.8), then the bridge structure can go through a given period (here, 60 years) without any maintenance activity. On the other hand, if the present live load capacity factor is low (C_{max}=1.5, C_p=1.0), the ability of maintenance options to suppress/reduce the deterioration becomes a significant factor in identifying an optimal plan. In this study, it was assumed that the option 'CP' can suppress the deterioration for 30 years, so two consecutive applications of the option 'CP' form an optimal maintenance plan in case of C_{max}=1.5, C_p=1.0. For cases where the present live load capacity factor is between the above two extreme values, the optimal plans are formed by combining preventative maintenance options appropriately.

2) There is an inverse relationship between the present live load capacity factor of the bridge structure and the values of cost and environmental score produced. In other words, as the present live load capacity factor becomes lower, the cost and environmental score of the optimal maintenance plans becomes larger.

3) The types of impacts considered, i.e. direct impacts only, indirect impacts only and both impacts, affect the selection of the optimal maintenance plans. When assuming that the AADT is equal to 60,000, the values of indirect impacts are much larger than those of direct impacts, hence the optimal maintenance plans based on either indirect only or both direct and indirect impacts are the same in all five cases.

4) Finally, in most cases, more than one optimal maintenance plan exists on the non-inferior curve (See Appendix D). In this situation, a single preferable maintenance plan can be chosen according to the decision maker's preference on cost and environmental score. The ranges of weighting factor for cost which make each maintenance plan optimal are presented in the last column of Table 7.4.

Table 7.4 Variation of optimal maintenance plans according to the maximum/present live load capacity factor values.

Maximum/present live load capacity factors	Impact type Considered	Optimal maintenance plans (Plan No. & Composition)	Original value		Normalised value		Range of WF_{cost} for optimal plan
			Cost	Envi. Score	Cost	Envi. Score	
C_{max}=1.8, C_p=1.8 (169 plans generated)	Direct impact only	(1) DN	0	0			
	Indirect impact only	(1) DN	0	0			
	Both impacts	(1) DN	0	0			
C_{max}=1.5, C_p=1.5 (256 plans generated)	Direct impact only	(96) CR-WP-WP-WP-DN	59.5	6.54	0	100	0.843~1.000
		(92) CR-WP-WP-CR-DN	63.2	5.72	9.3	50.3	0.357~0.843
		(1) CP-DN	100.0	4.89	100	0	0.000~0.357
	Indirect impact only	(1) CP-DN	5197.2	89.2			
	Both impacts	(1) CP-DN	5297.2	94.1			
C_{max}=1.5, C_p=1.3 (430 plans generated)	Direct impact only	(126) WP-WP-WP-WP-CP	85.8	12.25	0	100	0.741~1.000
		(47) WP-WP-WP-CP	86.7	10.41	11.7	66.7	0.552~0.741
		(48) WP-WP-CP-DN	88.7	8.57	38.7	33.3	0.352~0.552
		(4) WP-CP-DN	93.2	6.73	100	0	0.000~0.352
	Indirect impact only	(7) CP-WP-DN	8700.5	218.9	0	100	0.500~1.000
		(4) WP-CP-DN	9605.8	193.8	100	0	0.000~1.000
	Both impacts	(7) CP-WP-DN	8810.2	225.6	0	100	0.500~1.000
		(4) WP-CP-DN	9699.0	200.6	100	0	0.000~1.000
C_{max}=1.5, C_p=1.0 (355 plans generated)	Direct impact only	(1) CP-CP	135.8	9.780			
	Indirect impact only	(1) CP-CP	12203.8	348.6			
	Both impacts	(1) CP-CP	12339.6	358.4			
C_{max}=1.3, C_p=1.3 (298 plans generated)	Direct impact only	(3) CR-WP-CP	77.7	7.750	0	100	0.500~1.000
		(4) CR-CP-DN	80.7	5.910	100	0	0.000~0.500
	Indirect impact only	(14) CP-WP-DN	8700.5	218.9	0	100	0.500~1.000
		(8) WP-CP-DN	9605.8	193.8	100	0	0.000~0.500
	Both impacts	(14) CP-WP-DN	8810.2	225.6	0	100	0.500~1.000
		(8) WP-CP-DN	9699.0	200.6	100	0	0.000~0.500

7.3.4 Variation of optimal maintenance plans due to changes in traffic volume

In the above section, the AADT on the main route was assumed to be 60,000, and consequently the indirect impacts governed the total impacts. Here, the influence of the traffic volume on the choice of optimal maintenance plans is examined by varying the AADT from 20,000 to 70,000 and tracing the relative magnitude between direct and indirect impacts. For this, the maximum and present live load capacity factors of the bridge are assumed to be 1.5 and 1.3, respectively. The analysis results are summarised in Table 7.5 and the distribution of cost and environmental score of the maintenance plans generated in each case are presented in Appendix D.

From the fourth and fifth columns in Table 7.5 which show the original cost and environmental score of identified optimal maintenance plans, it is evident that as the traffic volume increases, the amount of indirect impacts and, accordingly, their importance in determining optimal maintenance plans increase. This can be clearly observed in Figure 7.7 where the indirect costs and environmental scores of the maintenance plan 'WP-CP-DN', which is optimal in all traffic volume cases, are compared. When the AADT is equal to 20,000, the indirect cost and environmental score represent 53% and -37% (negative value) of the total cost and environmental score, respectively; hence the total impacts are significantly affected by the direct impacts. Interestingly, if the traffic volume is small, the additional fuel consumption due to bridge maintenance activities and corresponding environmental score could decrease compared to the 'no works' situation. On the other hand, when the AADT is between 50,000 and 70,000, the values of indirect cost and environmental score are more than 98% and 93% of the total cost and environmental score, respectively; hence the total impacts are totally governed by indirect impacts. When the AADT is between 30,000 and 40,000, it is considered that the total cost is still governed by the indirect cost, but the total environmental score is affected by both impacts.

These differences in the relative magnitude between direct and indirect impacts due to traffic volume are well reflected in the resulting optimal maintenance plans. The third column in Table 7.5 shows that the same maintenance plans are selected as optimal in the above three ranges of traffic volume (20,000 / 30,000~40,000 / 50,000~70,000), respectively. Furthermore, when the AADT is equal to or over 30,000, the optimal maintenance plans based on both impacts and indirect impacts only are identical. This indicates that, unless the amount of traffic volume is quite small, the indirect impacts associated with traffic disruption could govern the total impacts and hence determine the types of optimal maintenance plans.

7.3.5 Conclusions

In this section, one preliminary analysis and a further two deterministic analyses have been undertaken. It is considered that the type of output from deterministic analysis and its interpretation in determining optimal maintenance plans were illustrated.

The analysis results imply that the optimal bridge maintenance plans in terms of sustainability can be influenced by a number of factors. The present condition of bridge structure, the ability of maintenance options to suppress/reduce deterioration, the impact types considered and the decision maker's preference regarding cost and environmental score are all significant factors in determining optimal maintenance plans. Of course, other factors such as the remaining service life of the bridge, the estimated unit cost and environmental score related to maintenance options, the works duration are also considered to be influential factors.

For reliable deterministic analysis results, the availability of accurate input data is absolutely essential. However, in reality the availability of such data is quite limited. Therefore, in the next section, as a way of not only treating input data uncertainty but also as a means of decision-making supporting, a range of probabilistic analysis studies will be undertaken.

Table 7.5 Variation of optimal maintenance plans with traffic volume in case of $C_{max}=1.5$, $C_p=1.3$.

Traffic volume	Impact type considered	Optimal maintenance plans (Plan No. & Composition)	Original value		Normalised value		Range of WF_{cost} for optimal plan
			Cost	Envi. Score	Cost	Envi. Score	
In all cases	Direct impact only	(126) WP-WP-WP-WP-CP	85.8	12.250	0	100	0.741~1.000
		(47) WP-WP-WP-CP	86.7	10.410	11.7	66.7	0.552~0.741
		(48) WP-WP-CP-DN	88.6	8.570	38.7	33.3	0.352~0.552
		(4) WP-CP-DN	93.2	6.730	100	0	0.000~0.352
AADT=20,000	Indirect impact only	(4) WP-CP-DN	106.6	-1.822	0	100	0.747 ~1.000
		(48) WP-WP-CP-DN	147.3	-2.631	4.8	85.9	0.687~0.747
		(42) WP-CR-CP-CN	155.7	-2.755	5.8	83.7	0.648~0.687
		(20) CR-CR-CP-DN	163.3	-2.850	6.7	82.1	0.523~0.648
		(13) DN-RE-CP-DN	794.5	-7.519	80.8	0.7	0.035~0.523
		(16) DN-RE-CP-CP	958.1	-7.559	100	0	0.000~0.035
	Both impacts	(4) WP-CP-DN	199.7	4.908	0	100	0.500~1.000
		(20) CR-CR-CP-DN	286.9	4.080	100	0	0.000~1.000
AADT=30,000	Indirect impact only	(4) WP-CP-DN	641.4	4.257			
	Both impacts	(4) WP-CP-DN	734.6	10.987			
AADT=40,000	Indirect impact only	(4) WP-CP-DN	2482.7	32.965			
	Both impacts	(4) WP-CP-DN	2575.9	39.695			
AADT=50,000	Indirect impact only	(7) CP-WP-DN	5344.0	121.493	0	100	0.500~1.000
		(4) WP-CP-DN	5804.9	98.761	100	0	0.000~1.000
	Both impacts	(7) CP-WP-DN	5453.7	128.223	0	100	0.500~1.000
		(4) WP-CP-DN	5898.1	105.491	100	0	0.000~1.000
AADT=60,000	Indirect impact only	(7) CP-WP-DN	8700.5	218.895	0	100	0.500~1.000
		(4) WP-CP-DN	9605.8	193.826	100	0	0.000~1.000
	Both impacts	(7) CP-WP-DN	8810.2	225.625	0	100	0.500~1.000
		(4) WP-CP-DN	9699.0	200.556	100	0	0.000~1.000
AADT=70,000	Indirect impact only	(7) CP-WP-DN	10980.9	311.481	0	100	0.500~1.000
		(4) WP-CP-DN	12250.1	299.351	100	0	0.000~1.000
	Both impacts	(7) CP-WP-DN	11090.6	318.211	0	100	0.500~1.000
		(4) WP-CP-DN	12343.3	306.081	100	0	0.000~1.000

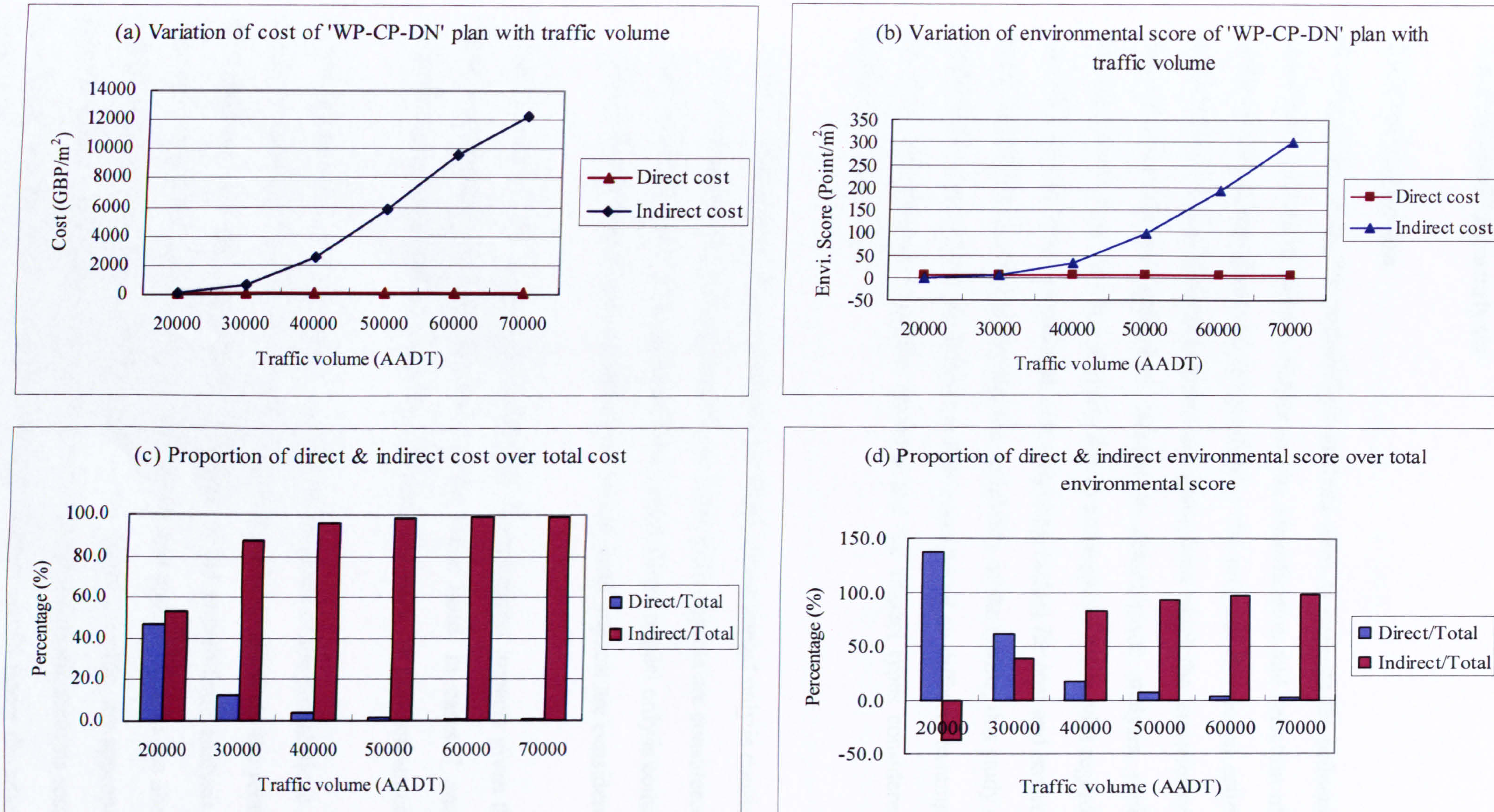


Figure 7.7 Variation of indirect impacts of a 'WP-CP-DN' plan with traffic volume

7.4 Probabilistic analysis

7.4.1 Introduction

In the present study, the probabilistic analysis aims to evaluate the influence of the uncertainty related to input variables on the identification and selection of optimal bridge maintenance plans. More specifically, the program developed estimates the relative frequency of optimal maintenance plans from which the 'superiority' of each optimal plan can be established. Similar to deterministic analysis, probabilistic analysis results may vary significantly due to assumptions made with regard to input variables, impact types considered, and weighting factors for cost and environmental score. Therefore, in order to explore the variability of the results, this study executes probabilistic analyses for the following four cases based on different assumptions on the scope of uncertain variables included and the impact types considered in the simulation. These are:

Case 1: Maintenance plans generated are fixed, direct impact only is considered.
Case 2: Maintenance plans generated are fixed, both impacts are considered.
Case 3: Maintenance plans generated are varied, direct impact only is considered.
Case 4: Maintenance plans generated are varied, both impacts are considered.

In cases 1 and 2, the uncertainties related to direct/indirect impacts given the same fixed maintenance plans are treated. On the other hand, in cases 3 and 4, the uncertainties associated with generating maintenance plans are also accounted for.

In the section 6.1.3, it was proposed that the convergence of the probabilistic analysis results is controlled by the CP and CN values. In order to illustrate the relationship between these two values and the convergence of the probabilistic analysis results, this study considers ranges of CP and CN values and applies them to the above four probabilistic analysis cases. Based on the results, where possible, the appropriate CP and CN values which ensure the convergence of the probabilistic analysis results will be selected and the details of the probabilistic analysis results under the selected CP and CN values will be analysed.

7.4.2 Basic assumptions on uncertain variables

For probabilistic analysis, the distribution shape and their parameters of uncertain variables should be known. However, available data, particularly related to the change of performance index profile and environmental score, are quite limited at present. Therefore, in this study, it is assumed that all uncertain variables have a triangular distribution shape and their minimum, mode and maximum values are 1/2, 1.0 and 1.5 times of the specified values used in deterministic analysis. Exceptionally, the minimum, mode and maximum values for the maximum live load capacity factor are taken as 0.8, 1.0 and 1.2 times of the specified value (here, C_{max}=1.5) in order to prevent the maximum live load capacity factor generated during simulation from being less than the minimum value (here, C_{min}=0.91). The detailed data related to all input variables can be found in Appendix E where the input files for above four cases are presented.

7.4.3 Variation of the probabilistic analysis results according to CP and CN values

The figures chosen for specifying convergence criteria are 1%, 0.5% and 0.1% for CP and 5, 10 and 15 for CN, respectively. By combining them, nine pairs of convergence criteria are considered. Moreover, as an indicator for checking the convergence of the probabilistic analysis results, the frequencies of all optimal maintenance plans on the non-inferior curve, irrespective of the weighting factors for cost and environmental score, are taken into account.

In Tables 7.6 ~ 7.9, the variation of the frequencies of the optimal maintenance plans as a function of CP and CN values in the above four cases are summarised. In addition, the sample size required for satisfying convergence criteria, the number of global maintenance plans generated during simulations and the number of optimal maintenance plans produced are also presented in these Tables. In Table 7.8 dealing with Case 3, only thirteen main optimal maintenance plans whose frequencies are larger than 2% at least once are included for simplifying the table. Similarly, in Table 7.9 seventeen main optimal plans whose frequencies are larger than 1% at least once are summarised for the same purpose. Finally, the variation of the frequencies of the optimal maintenance plans in these cases is graphically shown in Figure 7.8. From Tables 7.6~7.9 and Figure 7.8, the following remarks can be made:

1) As the convergence criteria become stricter, a larger sample size is required. Furthermore, in Cases 3 and 4, the number of global maintenance plans, as well as the number of optimal maintenance plans, gets larger when the stricter convergence criteria are selected.

2) It seems that some main optimal plans which have much higher frequencies than others can be identified by applying relatively relaxed combinations of CP and CN values. In particular, if a single maintenance plan, like 'CP-DN' in Case 2, is clearly dominant, it would not be necessary to apply strict convergence criteria. On the other hand, for a robust definition of convergence such as no reversal in ranking as well as stability in relative frequencies being achieved, stricter convergence criteria, like CP=0.1% and CN=10, need to be applied.

3) It is difficult to specify an appropriate pair of CP and CN values applicable to all probabilistic analysis cases because the convergence is affected by a number of input variables and their probabilistic distribution shapes. However, as can be seen in Figure 7.8, it seems that if the CP value is 0.1% and the CN value is equal to or larger than 10, convergence in the strict sense can be ensured in all four cases. Therefore, in the following analyses, the values of 0.1% and 15 will be used for CP and CN, respectively.

Table 7.6 Variation of frequencies of the optimal maintenance plans according to CP and CN values in Case 1

Convergence criteria		CP=1%			CP=0.5%			CP=0.1%		
		CN=5	CN=10	CN=15	CN=5	CN=10	CN=15	CN=5	CN=10	CN=15
Sample size		44	59	107	99	123	170	321	475	480
No. of global maintenance plans generated		256	256	256	256	256	256	256	256	256
Number of optimal plans		7	8	9	9	9	11	11	11	11
No	Composition of Maintenance plan	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)
1	CR-WP-WP-WP-DN	27.01	26.52	24.55	24.43	24.27	24.66	25.41	25.55	25.66
2	CR-WP-WP-CR-DN	27.01	25.41	26.06	26.06	26.40	26.59	26.64	26.99	27.09
3	CP-DN	23.36	23.76	25.76	25.41	25.33	24.08	22.13	22.80	22.60
4	CR-WP-CR-CR-CR	5.84	6.08	5.45	5.86	5.07	5.59	5.74	5.43	5.45
5	WP-WP-WP-WP-DN	10.22	8.29	8.48	8.14	9.60	8.86	10.04	9.62	9.67
6	CR-WP-CR-WP-DN	1.46	1.66	0.91	0.98	0.80	0.77	0.51	0.48	0.48
7	CR-CP-DN	5.11	7.73	6.97	7.49	6.13	6.74	6.45	6.11	6.06
8	CR-CR-WP-WP-DN	0	0.55	0.91	0.65	1.07	1.16	1.54	1.37	1.36
9	WP-WP-WP-CR-DN	0	0	0.91	0.98	1.33	1.16	0.82	0.82	0.82
10	CR-CR-CR-WP-CR	0	0	0	0	0	0.19	0.41	0.55	0.54
11	CR-CR-WP-CR-CR	0	0	0	0	0	0.19	0.31	0.27	0.27
	Sum (%)	100	100	100	100	100	100	100	100	100

Table 7.7 Variation of frequencies of the optimal maintenance plans according to CP and CN values in Case 2

Convergence criteria		CP=1%			CP=0.5%			CP=0.1%		
		CN=5	CN=10	CN=15	CN=5	CN=10	CN=15	CN=5	CN=10	CN=15
Sample size		70	97	102	169	185	208	616	890	895
No. of global maintenance plans generated		256	256	256	256	256	256	256	256	256
Number of optimal plans		1	1	1	1	1	1	1	1	1
No	Composition of Maintenance plan	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)
1	CP-DN	100	100	100	100	100	100	100	100	100
	Sum (%)	100	100	100	100	100	100	100	100	100

Table 7.8 Variation of frequencies of the optimal maintenance plans according to CP and CN values in Case 3

Convergence criteria		CP=1%			CP=0.5%			CP=0.1%		
		CN=5	CN=10	CN=15	CN=5	CN=10	CN=15	CN=5	CN=10	CN=15
Sample size		53	117	122	112	181	289	457	686	796
Number of plans generated		4289	6242	6506	6238	6837	7360	8061	10571	10729
Number of optimal plans		46	59	62	58	72	94	105	128	133
No	Composition of Maintenance plan	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)
1	CR-CP-DN	17.31	16.38	16.18	16.44	14.32	13.61	13.24	13.38	13.27
2	CR-WP-WP-WP-DN	6.73	6.47	6.22	6.39	6.17	4.89	5.11	4.83	4.82
3	CR-WP-WP-DN	6.73	5.6	5.39	5.94	4.69	4.01	4.8	5.23	5.06
4	WP-WP-WP-DN	5.77	5.6	5.39	5.02	5.43	5.24	4.8	4.24	4.46
5	CR-WP-DN	5.77	4.74	4.98	4.57	5.19	5.24	4.9	4.5	4.46
6	WP-WP-DN	5.77	5.6	5.81	5.48	4.69	4.54	4.28	3.91	3.63
7	DN	4.81	6.9	6.64	7.31	5.43	5.06	5.53	5.3	5.42
8	WP-WP-WP-WP-DN	3.85	3.02	3.32	3.2	2.72	2.62	3.02	3.18	3.15
9	CP-DN	3.85	6.03	6.22	5.94	7.9	7.16	6.88	6.56	7.02
10	CR-WP-CP-DN	1.92	2.16	2.07	2.28	2.22	1.92	2.29	2.72	2.56
11	CR-WP-CP	1.92	2.16	2.07	1.83	2.96	2.97	2.71	2.78	2.68
12	CR-WP-WP-CR-DN	1.92	2.16	2.07	1.83	2.47	2.27	2.09	1.85	2.08
13	CR-CR-DN	1.92	2.59	2.49	2.28	2.22	2.09	2.09	2.05	1.9
Sum (%)		68.27	69.41	68.85	68.51	66.41	61.62	61.74	60.53	60.51

Table 7.9 Variation of frequencies of the optimal maintenance plans according to CP and CN values in Case 4

Convergence criteria		CP=1%			CP=0.5%			CP=0.1%		
		CN=5	CN=10	CN=15	CN=5	CN=10	CN=15	CN=5	CN=10	CN=15
Sample size		87	146	151	163	174	216	790	839	844
No. of global maintenance plans generated		4689	6038	6054	6062	6070	6382	9248	9248	9296
Number of optimal plans		16	18	18	18	18	22	34	35	35
No	Composition of Maintenance plan	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)	Freq. (%)
1	CP-WP-DN	27.27	27.78	28.49	28.79	29.52	28.19	25.95	26.1	26.01
2	CP-DN	24.24	19.44	19.35	19.7	19.52	20.85	22.78	22.71	22.75
3	WP-CP-DN	16.16	16.67	16.67	16.16	15.71	14.29	16.84	16.73	16.72
4	DN	6.06	7.78	7.53	7.58	7.62	7.72	9.22	9.16	9.1
5	WP-WP-DN	9.09	6.67	6.99	7.07	7.14	6.95	4.13	3.98	3.96
6	WP-CP-WP-DN	2.02	5	4.84	4.55	4.29	4.63	3.18	3.19	3.17
7	WP-CR-DN	2.02	1.67	1.61	2.02	2.38	1.93	2.86	2.69	2.67
8	CR-CP-DN	1.01	2.22	2.15	2.53	2.38	1.93	2.12	2.29	2.27
9	CP-WP-WP-DN	1.01	2.78	2.69	2.53	2.38	2.7	2.22	2.09	2.18
10	WP-DN	3.03	2.22	2.15	2.02	1.9	2.32	1.91	1.89	1.88
11	CR-DN	1.01	1.11	1.08	1.01	0.95	1.16	1.38	1.49	1.58
12	CP-CR-DN	2.02	1.67	1.61	1.52	1.9	1.54	1.38	1.39	1.38
13	CP-CP-DN	0	0	0	0	0	0.39	0.95	1.00	1.09
14	WP-WP-CP-DN	1.01	1.11	1.08	1.01	0.95	0.77	0.74	0.8	0.79
15	CP-CP	2.02	1.11	1.08	1.01	0.95	1.16	0.85	0.8	0.79
16	CR-WP-DN	1.01	1.11	1.08	1.01	0.95	1.16	0.42	0.5	0.49
17	CR-CP-WP	1.01	0.56	0.54	0.51	0.48	0.39	0.11	0.1	0.1
Sum (%)		100	98.9	98.94	99.02	99.02	98.08	97.04	96.91	96.93

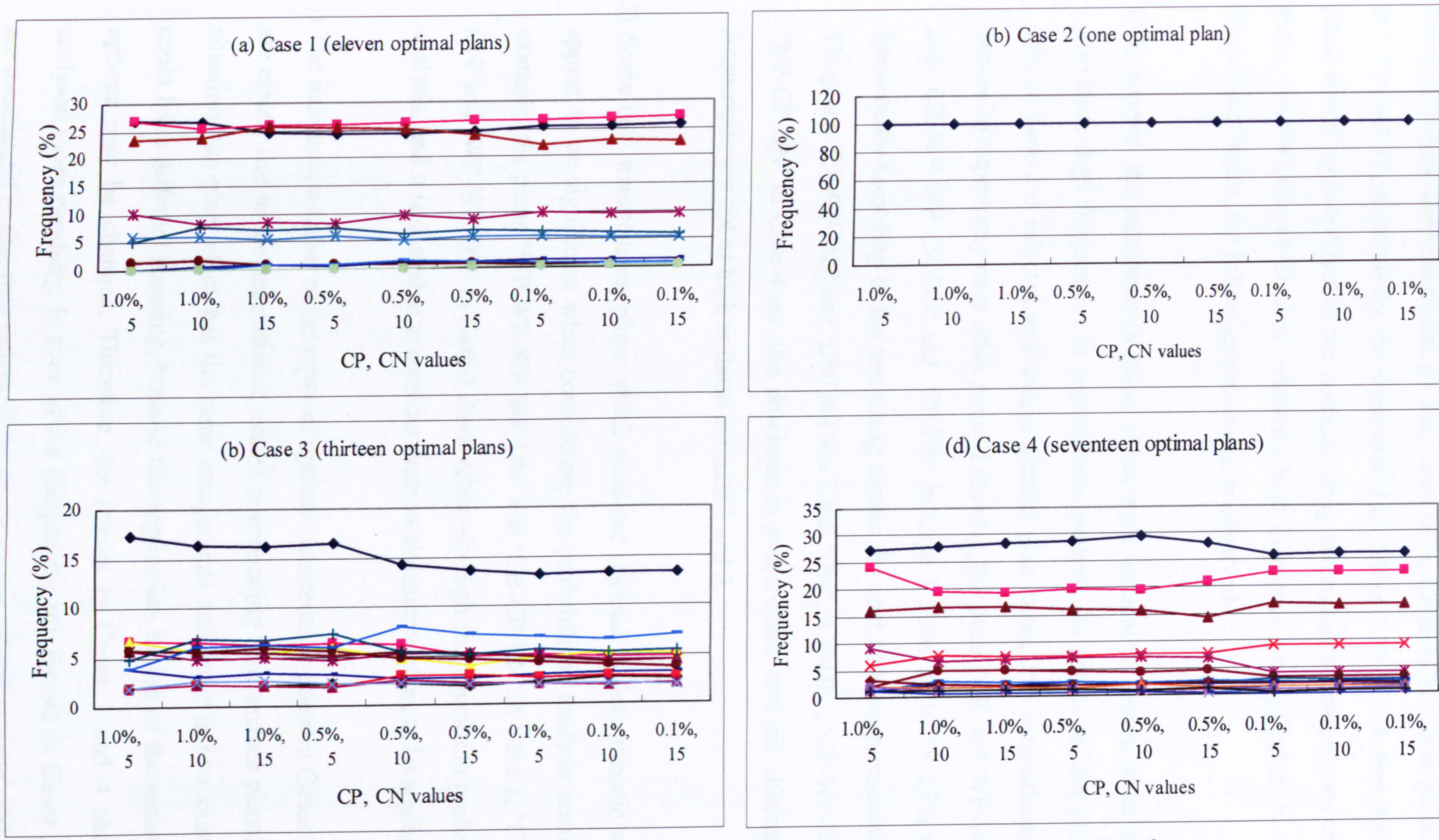


Figure 7.8 Variation of frequencies of optimal plans according to CP and CN values

7.4.4 Probabilistic analysis results when CP=0.1% and CN=15

The probabilistic analysis results for four cases when CP and CN values are set equal to 0.1% and 15, respectively, are summarised in Tables 7.10 ~ 7.13. For clarity, the plans which were optimal in the corresponding deterministic analysis are coloured green, and the cells which show relatively high frequency are highlighted in orange. From these Tables, the following points can be observed.

1) In general, the maintenance plans which were optimal in deterministic analysis also have high frequencies in probabilistic analysis. In particular, the plan 'CP-DN' in Case 2 is selected as a unique optimal plan during 895 simulations, which proves its superiority over other plans. Likewise, the plans 'CR-WP-WP-WP-DN' and 'CR-WP-WP-CR-DN' and 'CP-DN' in Case 1 show up to 58~67% relative frequencies according to the weighting factors for cost and environmental score. The plans 'CR-CP-DN' and 'DN' in Case 3 and 'DN', 'CP-DN', 'CP-WP-DN' and 'WP-CP-DN' in Case 4 are also dominant in probabilistic analysis although their frequencies are not as high as those in Cases 1 and 2.

2) Some new maintenance plans which were not optimal in deterministic analysis appear to be significant when considering the probabilistic analysis results. For example, the plans 'WP-WP-WP-WP-DN' and 'CR-CP-DN' in Case 1, 'CR-WP-DN' and 'WP-WP-DN' in Case 3 show relatively high frequencies in probabilistic analysis, and it is desirable to consider them as alternative plans to be applied.

3) The increased number of the types of optimal maintenance plans in Cases 3 and 4 are mainly due to the uncertainties related to generating maintenance plans. In this situation, the plan which has the same components and order in two simulations could have different meaning, because the application timing of the maintenance options may be changed. Therefore, the results in Cases 3 and 4 should be analysed more carefully. In spite of the complexity, the figures in Cases 3 and 4 are meaningful in that they reflect all the uncertainties related to sustainable bridge management proposed in this study.

Table 7.10 Probabilistic analysis results (Case 1: Maintenance plans are fixed and direct impact only is considered)

Order	Plan Number	Composition of Maintenance plan	WF_C =1.0 WF_E =0.0		WF_C =0.75 WF_E =0.25		WF_C =0.5 WF_E =0.5		WF_C =0.25 WF_E =0.75		WF_C =0.0 WF_E =1.0		All plans	
			Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
1	96	CR-WP-WP-WP-DN	292	60.83	153	31.88	82	17.08	1	0.21	-	-	377	25.66
2	92	CR-WP-WP-CR-DN	19	3.96	203	42.29	282	58.75	151	31.46	82	17.08	398	27.09
3	1	CP-DN	16	3.33	16	3.33	16	3.33	283	58.96	323	67.29	332	22.60
4	123	WP-WP-WP-WP-DN	134	27.92	85	17.71	27	5.63	8	1.67	9	1.88	142	9.67
5	8	CR-CP-DN	9	1.88	13	2.71	49	10.21	6	1.25	-	-	89	6.06
6	77	CR-CR-WP-WP-DN	8	1.67	8	1.67	5	1.04	3	0.63	11	2.29	20	1.36
7	71	CR-CR-CR-WP-CR	2	0.42	1	0.21	2	0.42	1	0.21	5	1.04	8	0.54
8	85	CR-WP-CR-CR-CR	-	-	1	0.21	13	2.71	26	5.42	39	8.13	80	5.45
9	121	WP-WP-WP-CR-DN	-	-	-	-	4	0.83	-	-	-	-	12	0.82
10	88	CR-WP-CR-WP-DN	-	-	-	-	-	-	1	0.21	7	1.46	7	0.48
11	74	CR-CR-WP-CR-CR	-	-	-	-	-	-	-	-	4	0.83	4	0.27
Sum			480	100	480	100	480	100	480	100	480	100	1469	100

Table 7.11 Probabilistic analysis results (Case 2: Maintenance plans are fixed and both impacts are considered)

Order	Plan Number	Composition of Maintenance plan	WF_C =1.0 WF_E =0.0		WF_C =0.75 WF_E =0.25		WF_C =0.5 WF_E =0.5		WF_C =0.25 WF_E =0.75		WF_C =0.0 WF_E =1.0		All plans	
			Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
1	1	CP-DN	895	100	895	100	895	100	895	100	895	100	895	100
Sum			895	100	895	100	895	100	895	100	895	100	895	100

Table 7.12 Probabilistic analysis results (Case 3: Maintenance plans are changed and direct impact only is considered)

Order	Plan Number	Composition of Maintenance plan	WF_C =1.0 WF_E =0.0		WF_C =0.75 WF_E =0.25		WF_C =0.5 WF_E =0.5		WF_C =0.25 WF_E =0.75		WF_C =0.0 WF_E =1.0		All plans	
			Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
1	4	CR-CP-DN	41	5.15	49	6.16	73	9.17	176	22.11	174	21.86	223	13.27
2	3627	DN	91	11.43	91	11.43	91	11.43	91	11.43	91	11.43	91	5.42
3	100	CR-WP-WP-WP-DN	63	7.91	59	7.41	48	6.03	17	2.14	15	1.88	81	4.82
4	2992	CR-WP-WP-DN	60	7.54	65	8.17	55	6.91	35	4.4	30	3.77	85	5.06
5	49	WP-WP-WP-DN	66	8.29	55	6.91	41	5.15	23	2.89	25	3.14	75	4.46
6	2982	CR-WP-DN	41	5.15	47	5.9	59	7.41	41	5.15	37	4.65	75	4.46
7	2985	WP-WP-DN	57	7.16	51	6.41	38	4.77	24	3.02	24	3.02	61	3.63
8	141	WP-WP-WP-WP-WN	46	5.78	37	4.65	26	3.27	9	1.13	10	1.26	53	3.15
9	3630	CP-DN	10	1.26	11	1.38	10	1.26	96	12.06	113	14.2	118	7.02
10	31	CR-WP-CP-DN	19	2.39	25	3.14	39	4.9	9	1.13	4	0.5	43	2.56
11	2983	CR-WP-CP	22	2.76	24	3.02	28	3.52	4	0.5	4	0.5	45	2.68
12	3020	CR-WP-WP-CR-DN	3	0.38	13	1.63	21	2.64	6	0.75	4	0.5	35	2.08
13	3631	CR-CR-DN	2	0.25	2	0.25	2	0.25	32	4.02	32	4.02	32	1.9
Sub sum of above thirteen plans			521	65.45	529	66.46	531	66.71	563	70.73	563	70.73	1017	60.51
Total sum of all (114) optimal plans			796	100	796	100	796	100	796	100	796	100	1680	100

Table 7.13 Probabilistic analysis results (Case 4: Maintenance plans are changed and both impacts are considered)

Order	Plan Number	Composition of Maintenance plan	WF_C =1.0 WF_E =0.0		WF_C =0.75 WF_E =0.25		WF_C =0.5 WF_E =0.5		WF_C =0.25 WF_E =0.75		WF_C =0.0 WF_E =1.0		All plans	
			Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
1	10	CP-WP-DN	257	30.45	257	30.45	257	30.45	157	18.6	157	18.6	263	26.01
2	1827	CP-DN	229	27.13	229	27.13	229	27.13	228	27.01	228	27.01	230	22.75
3	7	WP-CP-DN	59	6.99	59	6.99	59	6.99	168	19.91	168	19.91	169	16.72
4	1824	DN	92	10.9	92	10.9	92	10.9	92	10.9	92	10.9	92	9.1
5	1834	WP-WP-DN	39	4.62	39	4.62	39	4.62	39	4.62	39	4.62	40	3.96
6	48	WP-CP-WP-DN	19	2.25	19	2.25	19	2.25	26	3.08	26	3.08	32	3.17
7	1833	WP-CR-DN	27	3.2	27	3.2	27	3.2	15	1.78	15	1.78	27	2.67
8	4	CR-CP-DN	14	1.66	14	1.66	15	1.78	19	2.25	19	2.25	23	2.27
9	67	CP-WP-WP-DN	21	2.49	21	2.49	21	2.49	5	0.59	5	0.59	22	2.18
10	1826	WP-DN	19	2.25	19	2.25	19	2.25	19	2.25	19	2.25	19	1.88
11	1825	CR-DN	15	1.78	15	1.78	15	1.78	15	1.78	15	1.78	16	1.58
12	8	CP-CR-DN	14	1.66	14	1.66	14	1.66	11	1.3	11	1.3	14	1.38
13	11	CP-CP-DN	8	0.95	8	0.95	8	0.95	10	1.18	10	1.18	11	1.09
14	42	WP-WP-CP-DN	2	0.24	2	0.24	1	0.12	7	0.83	7	0.83	8	0.79
15	479	CP-CP	8	0.95	8	0.95	8	0.95	8	0.95	8	0.95	8	0.79
16	1830	CR-WP-DN	4	0.47	4	0.47	4	0.47	5	0.59	5	0.59	5	0.49
17	1832	CR-CP-WP	1	0.12	1	0.12	1	0.12	1	0.12	1	0.12	1	0.1
Sub sum of above seventeen plans			828	98.11	828	98.11	828	98.11	825	97.74	825	97.74	980	96.93
Total sum of all (35) optimal plans			844	100	844	100	844	100	844	100	844	100	1011	100

From Tables 7.10~7.13 which show the relative frequencies of optimal plans, it was possible to identify the main optimal plans. However, given the features of the developed methodology, it is also possible to investigate the probabilistic distributions of the main attributes of the maintenance plans, i.e. cost and environmental score, and, where possible, use this information in decision-making. In order to illustrate this aspect, two main optimal plans in Case 1, namely 'CR-WP-WP-WP-DN' and 'CP-DN' are examined herein. The relative frequency diagrams for cost and environmental score are plotted in Figure 7.9 (a) and (b), respectively. In addition, their main probabilistic properties, i.e. mean (μ), standard deviation (σ) and coefficient of variation (COV=σ / μ expressed as percentage) values, are also given in these plots. On the other hand, in Figure 7.9 (c) and (d), the corresponding cumulative frequency distributions as a function of cost and environmental score are presented. From these Figures, the following points can be observed.

1) The frequency distributions have, in all cases, an approximate triangular shape. This is related to the fact that the distribution shapes for unit cost and environmental score of maintenance options were assumed to be triangular, hence influencing the shape of the output distributions. The coefficient of variation lies between 15~22% confirming the influence of uncertainty on output parameters.

2) The characteristics of these distributions can be utilised to determine cost and environmental score with which the corresponding maintenance plan are associated. Basically, the mean values shown in Figure 7.9 (a) and (b), which represent the first moment approximation of the distributions, can be used for predicting cost and environmental score to be paid or produced. However, this estimate may be acceptable only when the dispersion of the distribution, represented by COV, is not large. If the distribution shows considerable variation, as is the case here, the decision maker needs to take account of a wider range of cost and environmental score values as selectable alternatives and the choice may vary according to the availability of budget, environmental policy as well as

decision maker's willingness to reduce the risk (or increase confidence level) in performing maintenance activities successfully.

The cumulative frequency distributions shown in Figure 7.9 (c) and (d) can be utilised for determining cost and environmental score corresponding to the confidence level chosen by a decision maker. If a decision maker chooses a specific cumulative frequency, say 80% in the graphs, the corresponding cost and environmental score can be found. It means that the maintenance plans considered can be carried out with an 80% confidence level by paying or producing the cost and environmental score found. The higher the cumulative frequency chosen for cost and environmental score, the higher is the decision maker's confidence that the maintenance works are carried out successfully.

In summary, by adopting the approach shown in this section, it is possible to identify an optimal maintenance plan on a probabilistic basis as well as to find cost and/or environmental score to be paid and produced based on a confidence level chosen by the decision maker.

7.4.5 Conclusions

It seems that probabilistic analysis results can be used either for supporting deterministic analysis results by confirming the high frequencies of the optimal plans or for producing alternative optimal plans which do not appear in deterministic analysis. As can be seen in above case studies, the probabilistic analysis results are highly sensitive to the assumptions made in relation to the uncertain input variables. Therefore, it may be reasonable to execute several probabilistic analyses based on different assumptions for the uncertain input variables and find the most robust alternative under a wide range of assumptions.

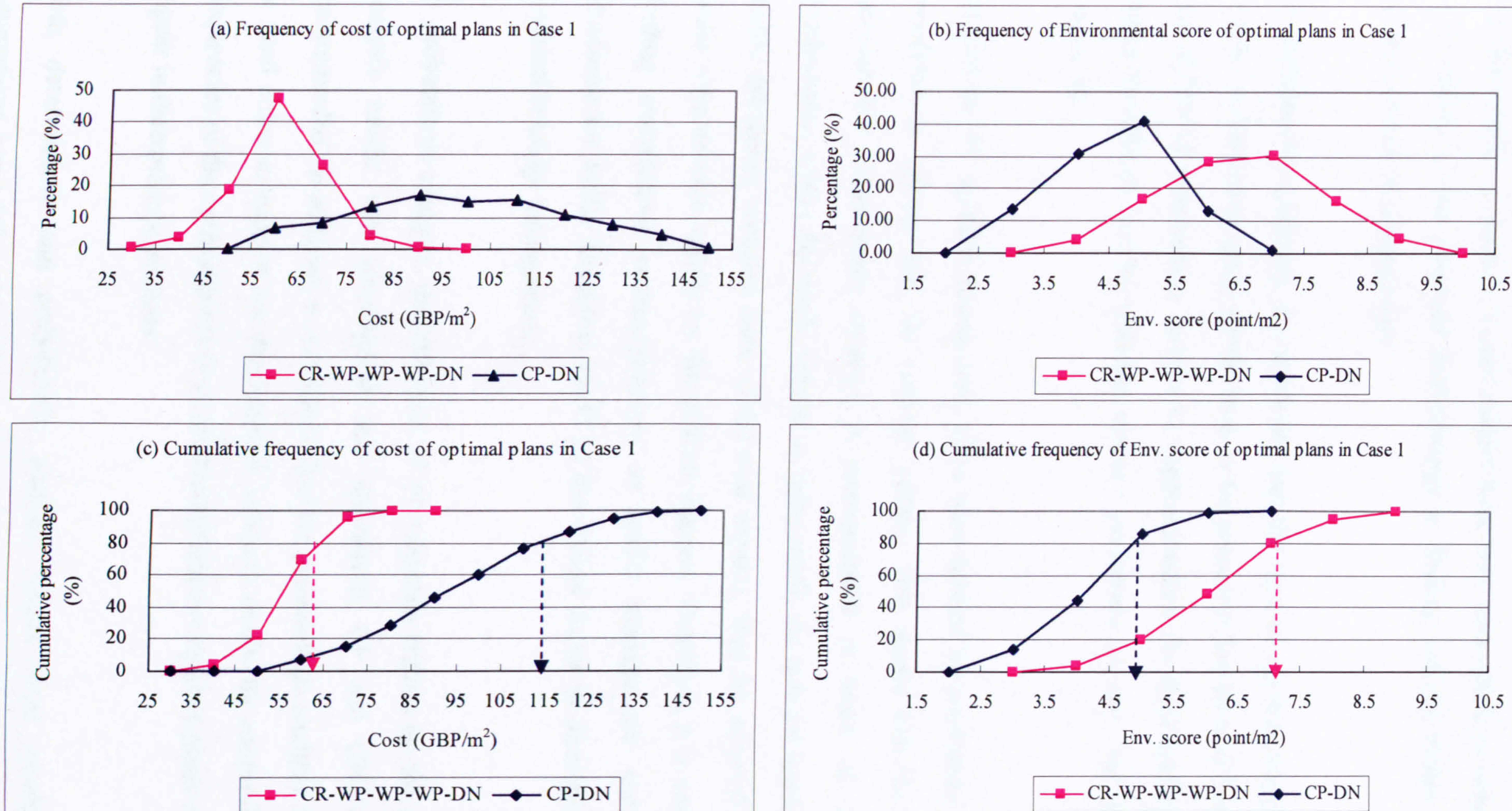


Figure 7.9 Probabilistic distributions of cost and environmental score of optimal plans in Case 1

7.5 Summary Conclusions

In this chapter, a number of case studies have been undertaken in order to illustrate the validity of the proposed methodology in finding optimal bridge maintenance plans in terms of sustainability.

In deterministic analysis, it was shown that the type of optimal maintenance plans can be varied due to many factors such as the present safety level of bridge structure, the ability of maintenance options to suppress/reduce the deterioration, the impact types considered and the decision maker's preference on cost and environmental score, etc.

In general, the optimal maintenance plans were formed by combining preventative maintenance options and 'do nothing' option. This shows that the adoption of preventative maintenance strategy is recommended in terms of sustainability. Furthermore, unless the traffic volume is quite small, the indirect impacts related to traffic disruption occupied most of the total impacts, thus the optimal maintenance plans were decided mainly by the indirect impacts. Therefore, it is considered that finding maintenance options/practices or traffic management methods which mimimise the traffic disruption could be the critical factor in decision making for sustainable bridge management.

In probabilistic analysis, the influence of convergence criteria on the probabilistic analysis results was investigated and appropriate CP and CN values were recommended. In addition, it was shown that the probabilistic analysis results could be used either to support the deterministic analysis results by confirming the high frequencies of the optimal plans or to produce alternative optimal plans which do not appear in deterministic analysis.

Both deterministic and probabilistic analysis results were sensitive to the assumptions, input data and weighting factors, etc. As shown throughout this chapter, the methodology developed in this study is quite flexible in dealing with input data and weighting factors. Therefore, it is considered that if reliable input data is available, the proposed methodology provides a powerful decision-making tool for identifying optimal bridge maintenance plans in terms of sustainability.

Chapter 8

Conclusions

8.1 Introduction

The principal objective of the present research was to develop and demonstrate the application of a decision-support tool in which optimal maintenance plans for existing bridge structures are determined on the basis of sustainability concepts.

The methodological framework adopted in this research depends on a variety of tools, such as generation of maintenance plans using time- and/or performance based approaches, whole life costing (WLC), life cycle assessment (LCA), multi-criteria decision aid/analysis (MCDA) and uncertainty analysis (UA). Both direct impacts from maintenance activities themselves, and indirect impacts related to traffic disruption have been taken into account. In order to satisfy these multi-dimensional requirements, a stand-alone computer programme was developed using the 'Fortran' programming language. The functions of this decision-support tool will be highlighted in section 8.2.

In order to demonstrate the validity of the proposed methodology and of the code itself, a series of deterministic and probabilistic analyses were executed for a simple example based on data collected and processed specifically for this study. Hence, it was possible to identify critical factors and preferable bridge management practices/options in terms of sustainability. They will be summarised in section 8.3. Finally, suggestions for future work will be given in section 8.4.

8.2 Main functions of the decision-making support tool

1) Generation of maintenance plans

The main improvement in developing maintenance plans within the present study is that all feasible maintenance plans are generated using either a time-based approach, i.e. based on effective life concept, or a performance-based approach, i.e. based on performance prediction and comparison with performance thresholds. In previous studies, a plan typically consisted of a single maintenance option applied repeatedly; hence the results obtained could only be used in a rather superficial comparison of the effectiveness of alternative options. However, the tool developed in this study generates plans by considering all feasible combinations of a number of maintenance options. It is believed that this leads to a structured and systematic approach within the bridge management decision-making process.

Additionally, the program developed is able to update bridge performance profiles based on inspection data. This feature facilitates the identification of optimal maintenance plans as a function of the actual present state of the bridge (following an inspection) or as a function of hypothetical future inspection outcomes.

2) Whole life costing

In the present study, the principle of whole life costing has been applied in relation to the economic criterion within sustainable bridge maintenance. Two types of cost, i.e. direct and indirect costs, are considered. Direct costs are the costs paid by bridge authorities in order to execute maintenance activities; the actual values used in the case studies have been determined based on several recent reports commissioned by the UK Highways Agency [75, 137, 139]. Indirect costs have been quantified by summing up delay time cost, as well as operating and accident costs, based on the principles and statistical data included in QUADRO [141] and COBA [142] manuals. These two cost components can be combined in any preferred combination by assigning appropriate weighting factors. Thus, different decision-making preferences can be readily accommodated, and their relative impact can be fully explored.

3) Life cycle assessment

The LCA methodology has been used in order to quantify the environmental impacts related to bridge maintenance activities. More specifically, Eco-indicator 95 and Eco-indicator 99 methodologies were selected as an LCIA methodology and databases in SimaPro program were consulted in order to quantify the environmental impacts related to the four maintenance options investigated herein. Direct environmental impacts have been calculated based on material input, delivery, electricity use and waste disposal, etc. On the other hand, indirect environmental impacts have been calculated from the additional fuel consumption arising from traffic disruption due to maintenance activities. The combination of direct and indirect environmental impacts can also be considered through *a priori* specified weighting factors, in a similar way to the methodology used for costs.

4) Multi-criteria decision aid/analysis (MCDA)

Two MCDA techniques, namely the Pareto principle and 'SMART' method, have been used in determining optimal maintenance plans. The Pareto principle has been applied to screen out (or eliminate) the so-called 'dominated' maintenance plans, i.e. those that have larger cost and environmental score than any other plan. Through the systematic application of this principle, several potentially optimal plans are identified. Each of these could be optimal, depending on the decision maker's preference. Thus, the 'SMART' method has then been used in order to quantify total preference. Both the cost and the environmental score of the potentially optimal plans were normalized and integrated using weighting factors; these factors, pertaining to economic and environmental criteria, depend on the decision maker's preference. The maintenance plan with the smallest overall weighted score is considered to be the overall optimum.

5) Uncertainty analysis

A crude Monte Carlo simulation technique has been adopted for modeling random uncertainty propagating through the different steps of the proposed methodology.

Thus, the influence of uncertain input data on the selection of optimal maintenance plans can be quantified. Based on a literature review, eight probabilistic distribution shapes have been included in the computer programme; if necessary, additional distribution shapes can be readily added. As is well known, results from Monte Carlo simulation are sensitive to the adopted sample size. Some heuristic convergence criteria have been developed and included in the programme so that the analyst can explore the sensitivity of the results to sample size effects.

8.3 Analysis results

8.3.1 Direct and indirect impacts of maintenance options

1) Bridge element replacement, undertaken as part of essential maintenance, is associated with much larger direct costs and environmental scores than any other maintenance option. Therefore, it would appear that delaying the application of essential maintenance options by means of appropriate preventative maintenance options is an effective way to reduce direct impacts.

2) As long as a positive traffic growth rate is assumed, indirect costs and environmental scores increase with time.

3) The combination of direct and indirect impacts related to bridge maintenance activities remains problematic, mainly because the magnitude of indirect impacts from traffic disruption vary substantially depending on actual traffic situation and traffic management scheme, uncertainty over works durations, etc. In general, unless the traffic volume is very small and the works duration is short, indirect impacts are much larger than direct impacts and this difference is accentuated as maintenance timing is delayed. Thus, indirect impacts could become the dominating factor in the bridge management process. It would appear that only where the traffic volume is small and works duration is short, it is sensible to combine both impacts within a single analysis.

8.3.2 Deterministic analysis results

1) In many cases, optimal maintenance plans consist of preventative maintenance options. An essential maintenance option has much larger direct and indirect impacts compared with preventative counterparts.

2) Optimal maintenance plans depend on the types of impact included, i.e. direct impacts only, indirect impacts only, or both. Furthermore, the present performance level of the bridge and the effectiveness of maintenance options in increasing/suppressing/reducing the performance profile also influence the composition of optimal plans. Finally, the length of the life-span considered is also a significant factor in determining optimal maintenance plans.

3) When more than one plan exists on the non-inferior curve, the decision maker's preference for economic and environmental impacts plays an important role in choosing the optimal plan. The programme has been developed in such a way so that the range of weighting factors that would make any particular plan optimal can be ascertained. Clearly, if only one maintenance plan exists on the non-inferior curve, this plan automatically becomes optimal regardless of preferences.

8.3.3 Probabilistic analysis results

1) It is difficult to specify general convergence criteria, i.e. CP and CN values, because convergence depends on the number of input variables and their probabilistic distribution shapes. However, it seems that if the purpose is to identify the main optimal plans, i.e. those which have much higher frequencies than others, then less strict convergence criteria can be adopted. On the other hand, for a full convergence to be achieved, strict convergence criteria need to be applied.

2) In general, maintenance plans found optimal in deterministic analysis, also exhibit high frequencies in probabilistic analysis. However, some additional maintenance

plans, not identified by deterministic analysis, also appear to be optimal based on the probabilistic analysis results. Therefore, it may be concluded that probabilistic analysis can be used to confirm results obtained deterministically but could also be used to widen the pool of optimal plans. It would therefore appear desirable to opt for probabilistic analysis where this is possible and where supporting data is of sufficiently good quality.

3) The frequencies of optimal maintenance plans vary according to the weighting factors for cost and environmental score. Therefore, in order to take full advantage of the decision-support function of the software package, it would seem logical to apply a different set of weighting factors for cost and environmental score and observe their influence on the estimated frequencies of optimal maintenance plans.

8.4 Future work

Future work is envisaged in two main areas: improvement of methodology and data collection. Some details are given below.

8.4.1 Improvement of methodology

The present study aims to develop a decision-support tool within the bridge management process, particularly in identifying optimal maintenance plans based on sustainability concepts. It is considered that the objective has been achieved to an acceptable degree. However, due to the complexity of the bridge management process and the multi-dimensional characteristics of sustainable development, the following three issues deserve further attention.

1) Evaluation of social impacts related to bridge maintenance activities

Among the three 'pillars' of sustainable development, social impacts related to bridge maintenance activities have not been considered in the present study. However, the ultimate aim of sustainable bridge management should be to satisfy simultaneously economic, environmental and social aspects. Therefore, the evaluation of social impacts related to bridge maintenance activities and integrating them into the methodology developed in the present study is a challenging future research topic.

2) Development of an appropriate LCIA methodology

In the present study, it was shown that LCA is an appropriate tool for calculating and analysing environmental impacts related to bridge maintenance activities. Furthermore, the characteristics of published LCIA methodologies were compared and, among them, Eco-indicator 95 and Eco-indicator 99 methodologies were selected for quantifying the environmental scores of maintenance options and fuel consumption. The main reason for choosing these methodologies is that, not only their normalisation factors reflect the European situations, but also environmental databases have been generated based on these methodologies. On the other hand; BRE's UK Ecopoints methodology has been developed based on the consensus of the UK construction industry, but the relevant databases do not, at present, include much environmental data that could be related to bridge maintenance activities. Therefore, in order to apply a UK specific LCIA methodology to bridge management, it is desirable to develop an appropriate LCIA methodology, and populate the relevant environmental databases. The BRE database could form the starting point in such an effort.

3) Improvement in developing maintenance plans

In the present study, a method has been developed with which feasible maintenance plans are automatically generated based either on an effective life concept or on a performance profile approach. However, there is still room for improvement in this area. For example, the method proposed herein cannot model the case in which several maintenance options are applied in tandem. Therefore, as future work, it is recommended that more realistic maintenance plans are developed by reviewing actual bridge management histories and hence elaborating the theoretical models.

8.4.2 Data collection for maintenance options

One of the most difficult aspects in the present study was the lack of relevant data.

Available data and information were collected as much as possible through literature review, personal communication and from some commercial packages such as QUADRO and SimaPro. However, the availability of appropriate data was quite limited.

On the cost side, data for the major maintenance options appear to be well documented, though not enough has been done to quantify their statistical variation.

In order to quantify the environmental score related to bridge maintenance options, the present study made some assumptions on material input and relied on existing databases. It would have been better if UK specific environmental data related to various maintenance options, for example the options presented in section 3.1, had been collected, but this task was considered too large to be undertaken within this project. It is believed that environmental data collection in this area should be led by the UK government and leading bridge management authorities, in collaboration with manufacturers, maintaining agents, etc.

Lastly, it was shown that the ability of maintenance options to delay bridge deterioration is a significant factor in choosing optimal maintenance plans. However, availability of relevant data is quite limited, and cannot be accumulated on a short-term basis. Thus systematic efforts are required over a long period of time in order to measure the change in performance due to various bridge maintenance options.

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Appendices

Appendix A: Environmental scores of four maintenance options

This Appendix presents the methodology used to derive the LCI for the four maintenance options under study. This is used in conjunction with the secondary data available with the SimaPro software. The resulting values are suitable for demonstrating the integrative methodology developed in Chapter 6 but are intended to be illustrative only.

1. Concrete repair

1) Assumption: Reinforced concrete is used to replace 0.1m depth of concrete. The repair area is assumed to be $1m^2$. The system diagram for concrete repair option, details of input data and resulting environmental scores are given below.

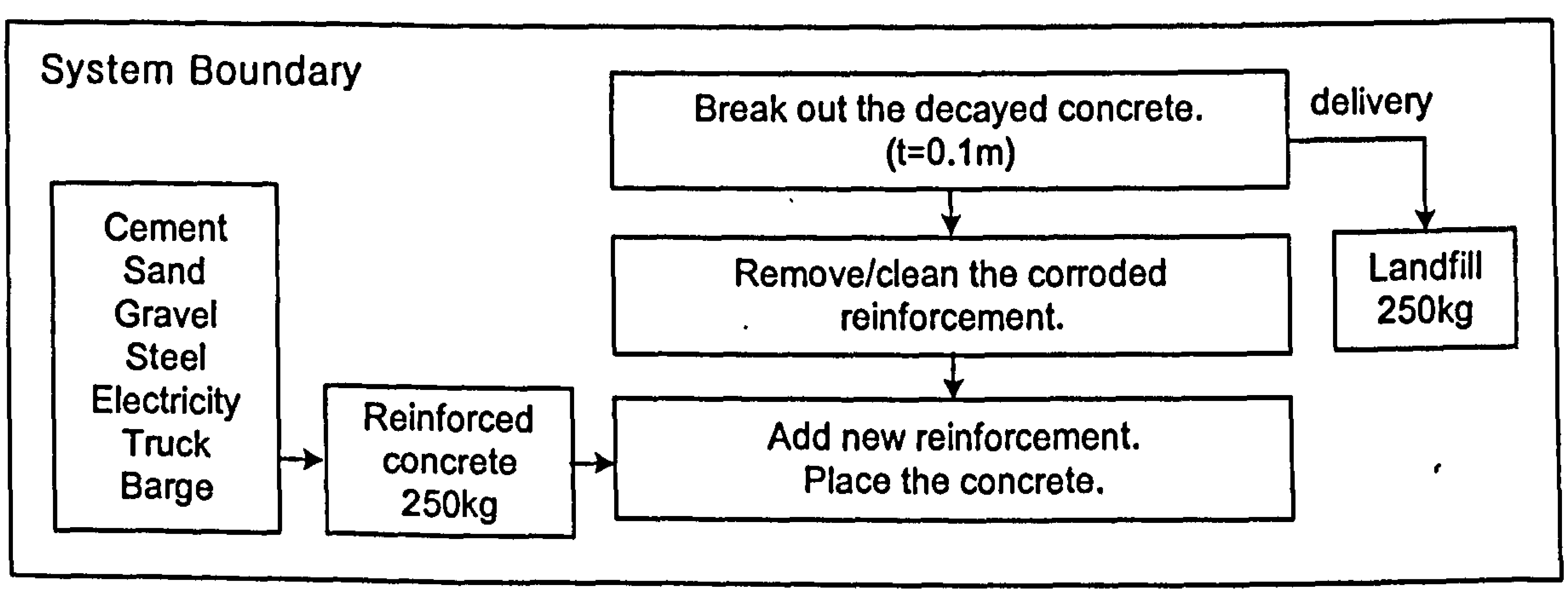


Figure A-1 System diagram of concrete repair option

2) Material input per $1m^2$ of deck surface area:

Reinforced concrete:

Volume of used reinforced concrete: $1m*1m*0.1m = 0.1m^3$

Unit weight of reinforced concrete: $25kN/m^3$

Weight of used reinforced concrete: $0.1*25=2.5kN$ ($\cong$ 250kg mass)

3) Waste disposal

Same amount of reinforced concrete (250kg) is buried in landfill.

4) Environmental scores by Eco-indicator 95 methodology

Material	Quantity	Unit environmental score	Environmental score
Reinforced concrete	250kg	8.37E-4/kg	0.2093
Waste disposal	250kg	2.64E-5/kg	0.0066
Sum			0.2159

5) Environmental scores by Eco-indicator 95 methodology

Material	Quantity	Unit environmental score	Environmental score
Reinforced concrete	250kg	4.06E-2/kg	10.1500
Waste disposal	250kg	1.23E-4/kg	0.0308
Sum			10.1808

2. Replacement of element

1) Assumption: Reinforced concrete is used to replace 0.6m depth of concrete. The repair area is assumed to be $1m^2$. The system diagram for replacement of element option, details of input data and resulting environmental scores are given below.

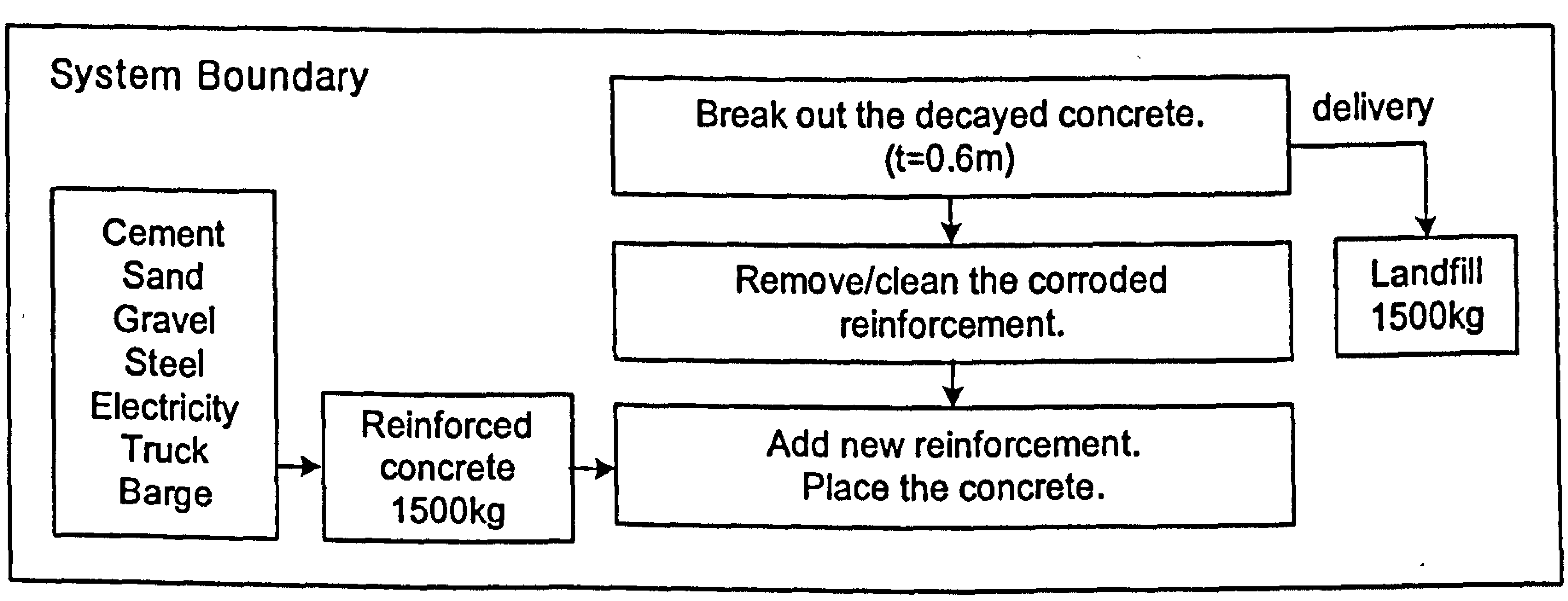


Figure A-2 System diagram for replacement of element option

2) Material input per $1m^2$ of deck surface area:

Reinforced concrete:

Volume of used reinforced concrete: 1m*1m*0.6m =0.6 m^3

Unit weight of reinforced concrete: 25kN/ m^3

Weight of used reinforced concrete: 0.6*25=15kN (≅ 1500kg mass)

3) Waste disposal

Same amount of reinforced concrete (1500kg) is buried in landfill.

4) Environmental scores by Eco-indicator 95 methodology

Material	Quantity	Unit environmental score	Environmental score
Reinforced concrete	1500kg	8.37E-4/kg	1.2555
Waste disposal	1500kg	2.64E-5/kg	0.0396
Sum			1.2951

5) Environmental scores by Eco-indicator 99 methodology

Material	Quantity	Unit environmental score	Environmental score
Reinforced concrete	1500kg	4.06E-2/kg	60.9000
Waste disposal	1500kg	1.23E-4/kg	0.1845
Sum			61.0845

3. Cathodic protection

1) Assumption

Titanium mesh with concrete overlay method is chosen as a bridge deck cathodic protection system. Details of this method were found in references [93] and [94]. Anode mesh used is ELGARD 210, which has following properties [93].

Nominal Anode Surface Area	0.21ft^2/ft^2
Substrate Composition	Titanium, Grade 1
Catalyst	Mixed Precious Metal Oxide
Width of Roll	4 ft
Length of Roll	250ft
Weight of Roll	45lbs/1000ft^2
Resistance Lengthwise	(4ft width) 0.014ohms/ft

In addition, it is assumed that 0.0508m (2inch) depth of plain concrete is used as an overlay and electricity of 110mA/m^2 is supplied for 30 years. The repair area is assumed to be 1m^2. The system diagram for cathodic protection option, details of input data and resulting environmental scores are given below.

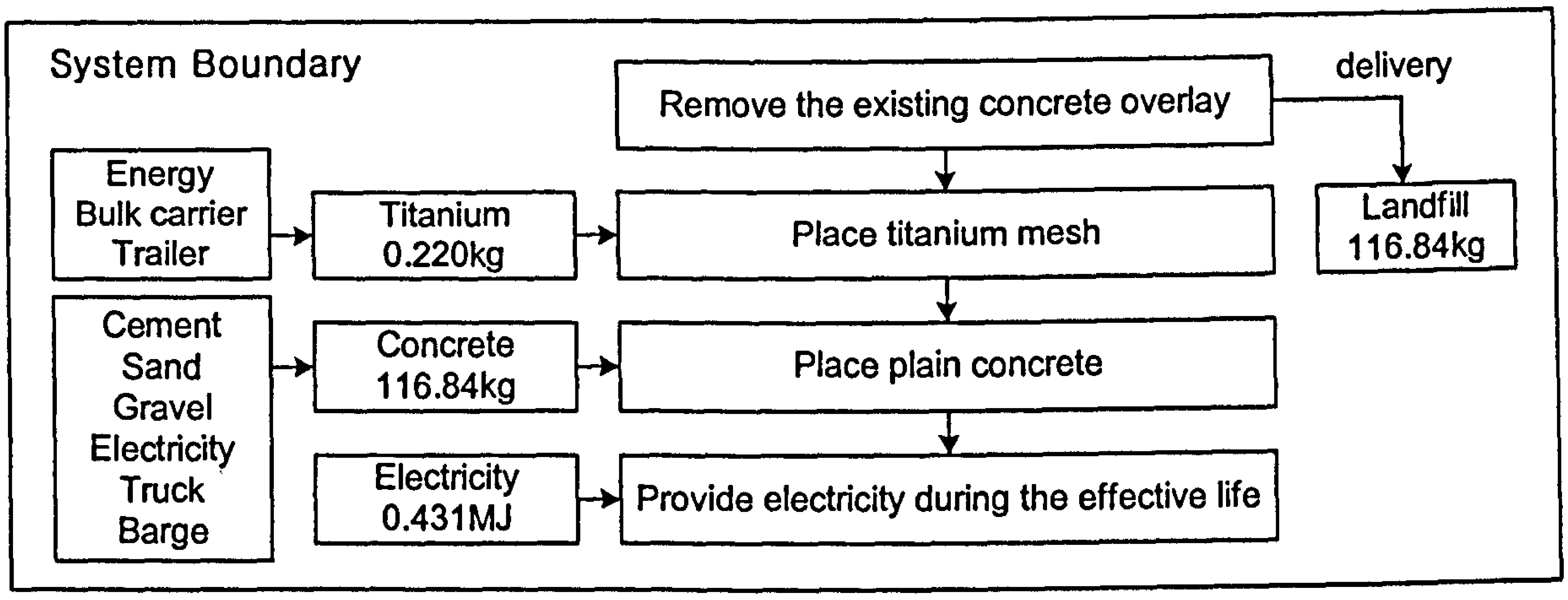


Figure A-3 System diagram of cathodic protection option

2) Material input per $1m^2$ of deck surface area

Titanium:

$45lbs/1000ft^2 = 0.219713kg/m^2$

Concrete overlay:

Volume of plain concrete: 1m*1m*0.0508m =0.0508 m^3

Unit weight of plain concrete: $23kN/m^3$

Weight of plain concrete: 0.0508*23=1.1684kN (≅ 116.84kg mass)

Electricity:

Current: $I=110mA/m^2=0.11A/m^2$

Mesh resistance: R=0.014ohms/ft length/4ft width= $0.037673686ohms/m^2$

Energy consumed in one second: $E=I^2Rt$= 0.11*0.037673686*1=4.55852E-4 Joule

Energy consumed for 30 years: E=4.55852E-4*60*60*24*365*30=431272 Joule

= 0.431272MJ

3) Waste disposal

It is assumed that existing concrete overlay (116.84kg) is buried in landfill. On the other hand, titanium mesh which acts as a cathodic protection anode is consumed by the anodic oxidation reaction, hence its waste disposal is not considered here.

4) Environmental score by Eco-indicator 95

Material	Quantity	Unit environmental score	Environmental score
Titanium	0.219713kg	0.0415/kg	0.00912
Concrete overlay	116.84kg	0.000671/kg	0.07840
Electricity	0.431272MJ	0.000327/MJ	0.00014
Waste disposal	116.8kg	2.64E-5/kg	0.00308
Sum			0.0908

5) Environmental score by Eco-indicator 99

Material	Quantity	Unit environmental score	Environmental score
Titanium	0.219713kg	1.93/kg	0.425
Concrete overlay	116.84kg	0.0381/kg	4.4516
Electricity	0.431272MJ	0.0105/MJ	0.00451
Waste disposal	116.8kg	1.23E-4/kg	0.0308
Sum			4.883

4. Waterproofing

1) Assumption

As an example of a bridge deck waterproofing system, the 'Eliminator' system developed by Stirling Lloyd Polychem Ltd is selected and its material inputs are quantified. According to BBA's certificate [195], the 'Eliminator' waterproofing system comprises three layers of primer, membrane and tack coat. The repair area is assumed to be $1m^2$. The system diagram for waterproofing option, details of input data and resulting environmental scores are given below.

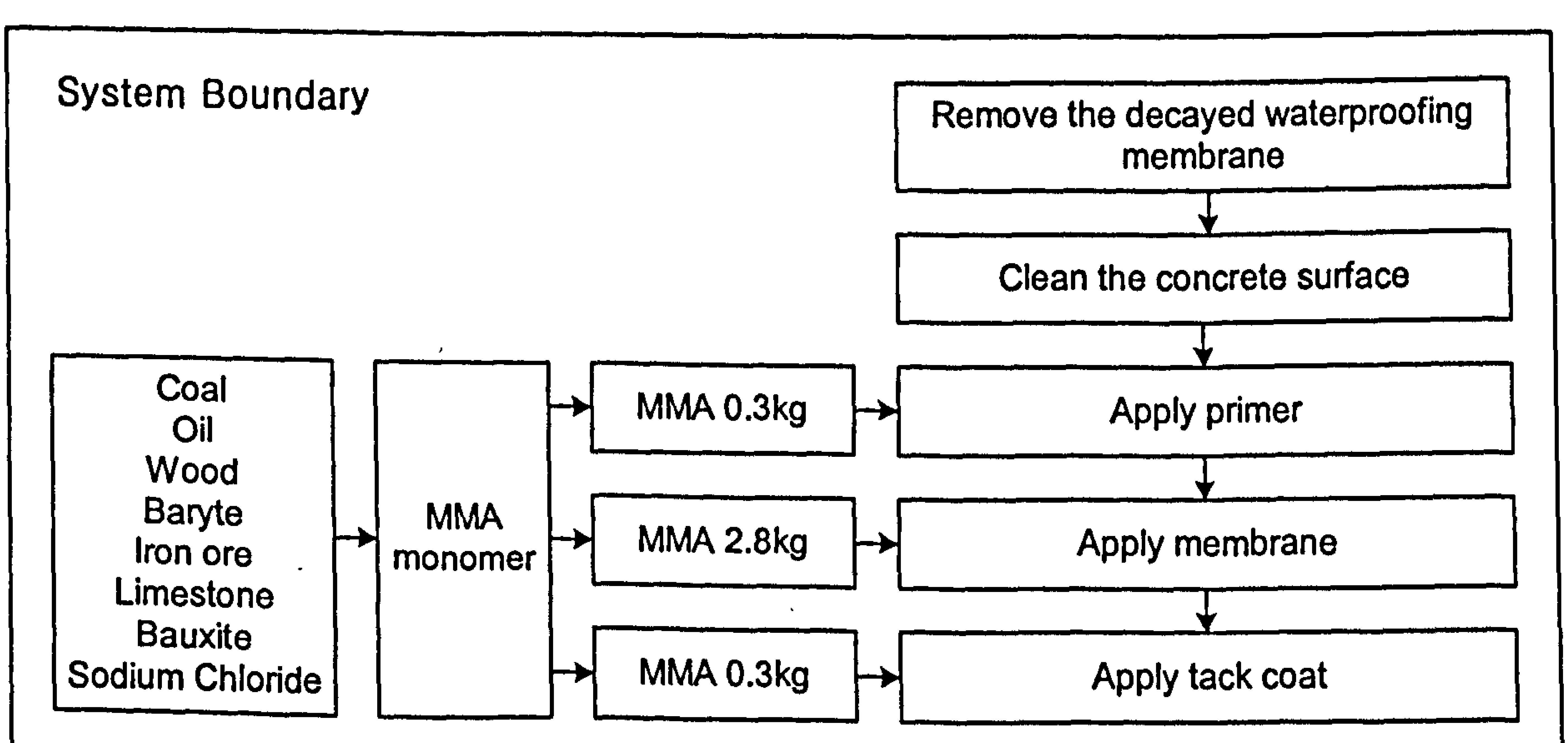


Figure A-4 System diagram of waterproofing option

2) Material input per 1m^2 of deck surface area:

Primer: 'Eliminator' has two kinds of primers. 'PA1 Primer' is a single-component, solvent-based methyl methacrylate resin solution, for use at temperatures above 5°C and is applied at a coverage rate of 0.15kg/ m^2 ~ 0.25 kg/ m^2. On the other hand, 'PAR1 Primer' is a single-component, solvent-free, highly reactive methyl methacrylate resin, for use at temperatures up to 30°C and is applied at a coverage rate of 0.20kg/m^2 ~ 0.30kg/ m^2.

Membrane: Membrane of 'eliminator' is a two-part, solvent-free, methyl methacrylate resin, comprising Part A and Part B. They are mixed with pre-weighed hardener powder and then applied at a coverage rate of 2.8kg/ m^2.

Tack coat: Tack coat is applied to the cured waterproofing membrane only in areas due to receive the additional protective layer (APL) of sand asphalt or hot-rolled asphalt (HRA). In this study, it is assumed that Tack Coat No 2 is used. It is a single-component, solvent-based, methyl methacrylate resin solution, orange pigmented, for use with additional protective layer (APL) of sand asphalt. It is applied either by spray, roller or brush at a coverage rate of 0.1 kg/ m^2 ~ 0.3 kg/m^2.

In summary, methyl methacrylate (MMA) is used as a main material for primer, membrane and tack coat. Therefore, from the quantity of MMA, the environmental score of waterproofing system will be calculated. Furthermore, it is difficult to remove the waterproofing system (only a few mm thick) at the end of life and no data regarding its environmental impacts due to disposal is available, hence its waste disposal is not taken into account in calculating the environmental impacts in this study.

3) Environmental score by Eco-indicator 95

Component	Material	Quantity	Unit environmental score	Environmental score
PAR1 primer	MMA	0.3kg	0.0071/kg	0.00213
Membrane	MMA	2.8kg	0.0071/kg	0.01988
Tack Coat No 2	MMA	0.3kg	0.0071/kg	0.00213
Sum				0.02414

4) Environmental score by Eco-indicator 99

Component	Material	Quantity	Unit environmental score	Environmental score
PAR1 primer	MMA	0.3kg	0.54/kg	0.162
Membrane	MMA	2.8kg	0.54/kg	1.512
Tack Coat No 2	MMA	0.3kg	0.54/kg	0.162
Sum				1.836

Appendix B: Flow charts for the developed software tool

In order to show the detail processes of the software tool developed in this study, several flow charts are given below. The first flow chart in Figure B-1 shows the overall processes while the other flow charts in Figures B-2 to B-6 show the detail processes of main subroutines included in the software tool.

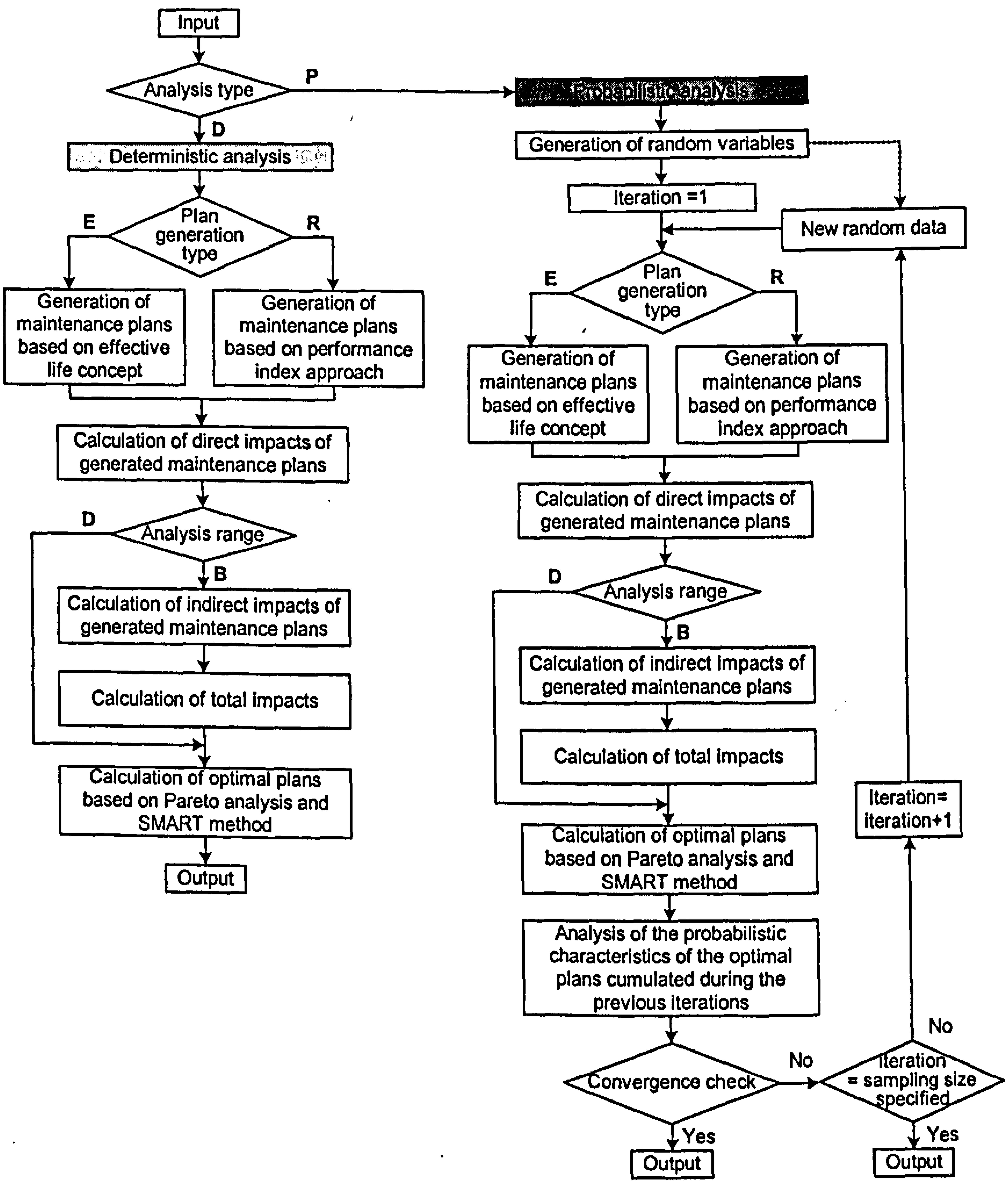
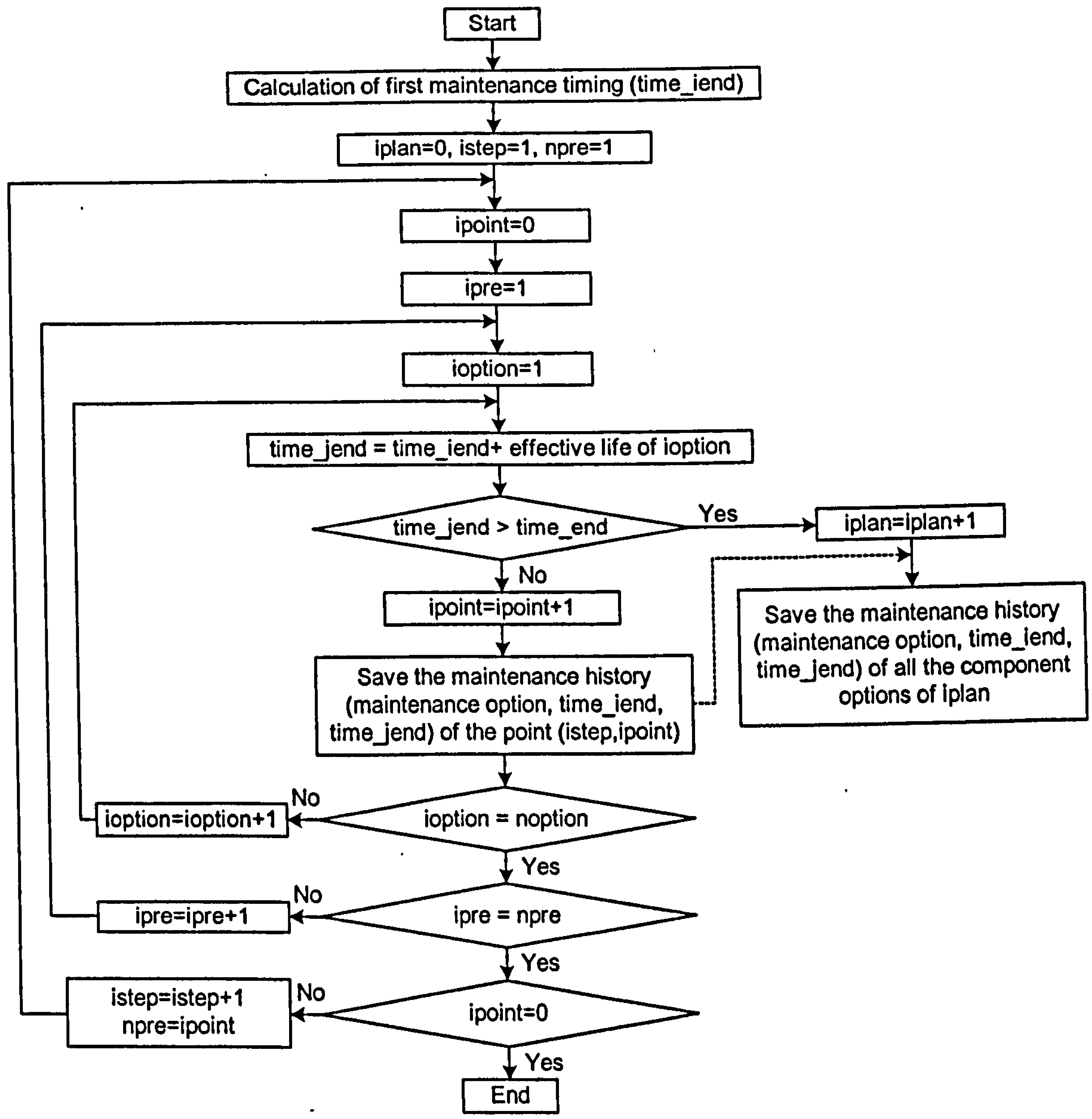
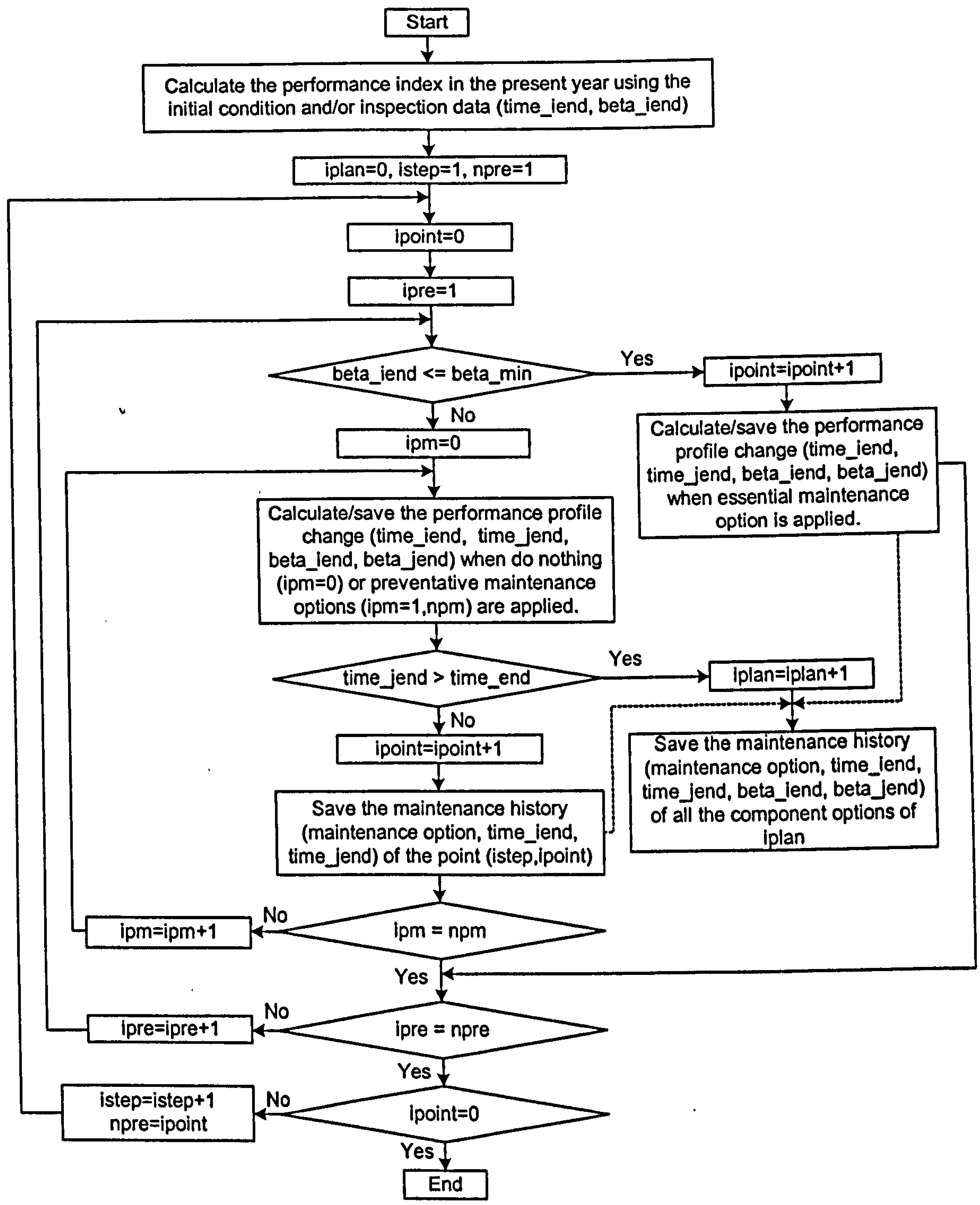


Figure B-1 Flow chart for the overall program



where,
iplan : index for generated plan number
istep : index for step number
ipoint : index for the number of points (branches) whose cumulative lives are less than the remaining service life
npre : number of ipoint in the previous step
noption : total number of maintenance options considered
ioption : index for the maintenance option

Figure B-2 Flow chart for the generation of maintenance plans based on the effective life concept



where,
iplan : index for generated plan number
istep : index for step number
ipoint : index for the number of points (branches) whose cumulative lives are less than the remaining service life
npre : number of ipoint in the previous step
noption : total number of maintenance options considered
ipm : index for the preventative maintenance option
npm : total number of preventative maintenance options
time_iend, time_jend : time values before and after one option is applied, respectively
beta_iend, beta_jend : performance index values before and after one option is applied, respectively.

Figure B-3 Flow chart for the generation of maintenance plans based on the performance index approach

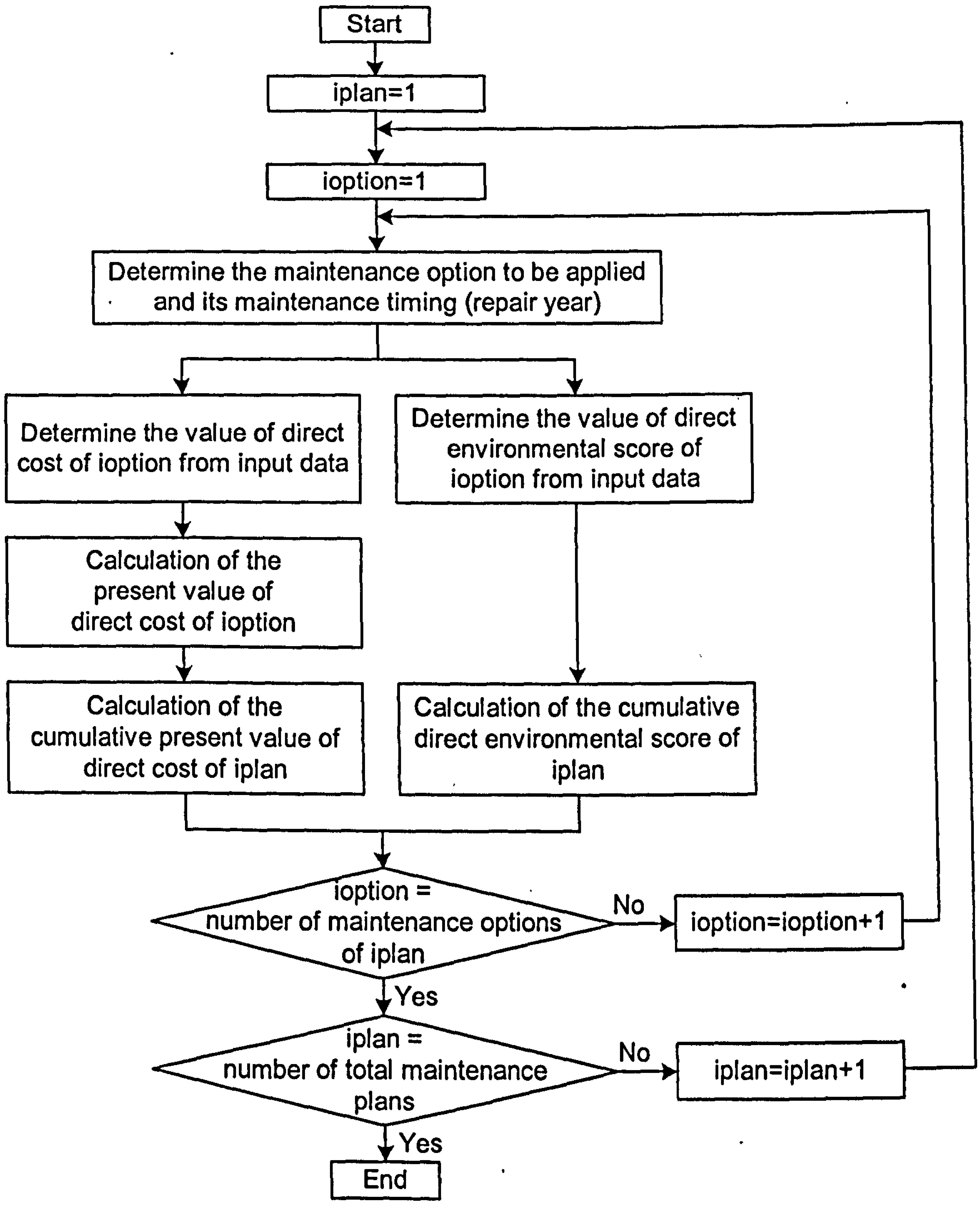


Figure B-4 Flow chart for the calculation of direct impacts of maintenance plans

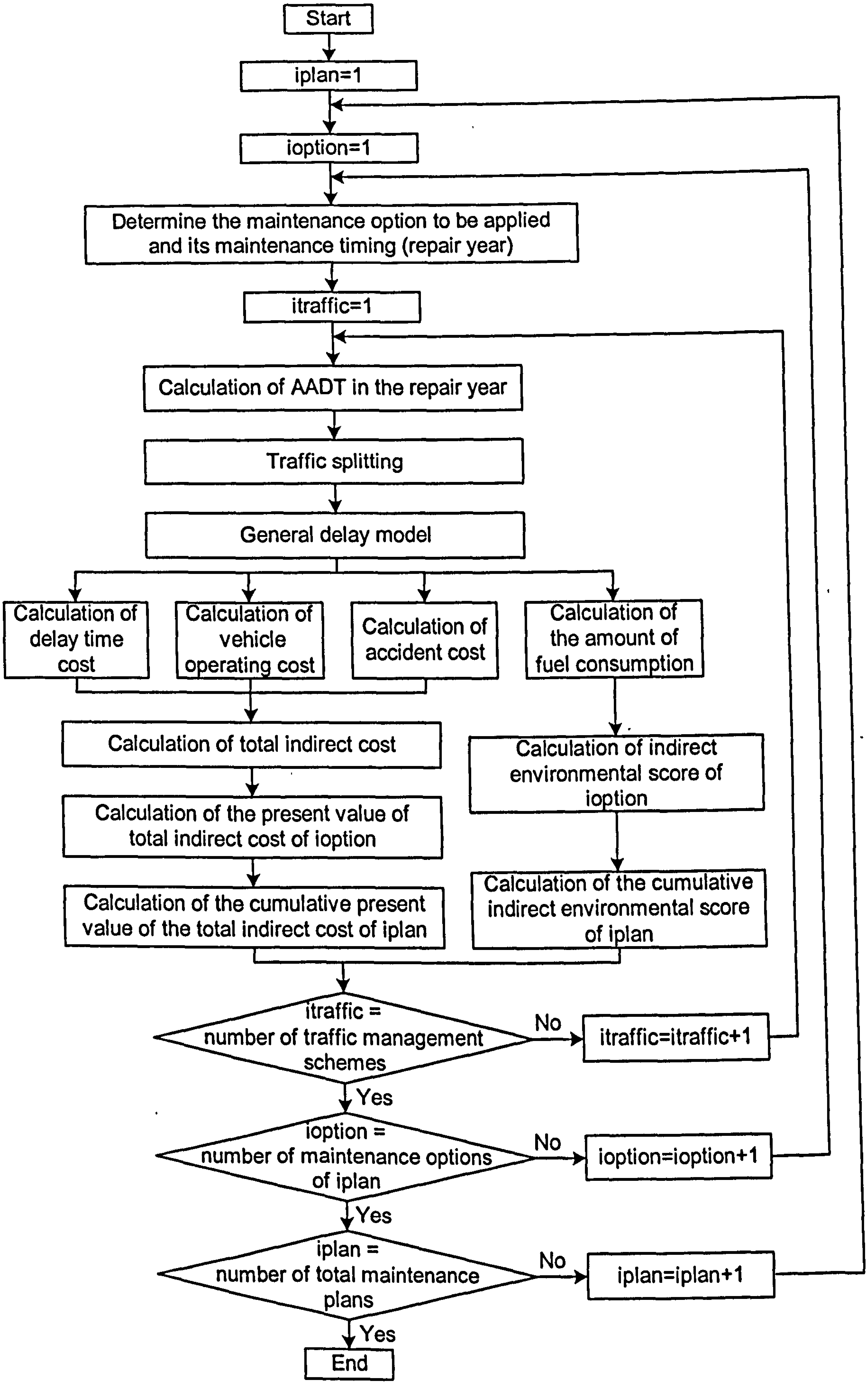


Figure B-5 Flow chart for the calculation of indirect impacts of maintenance plans

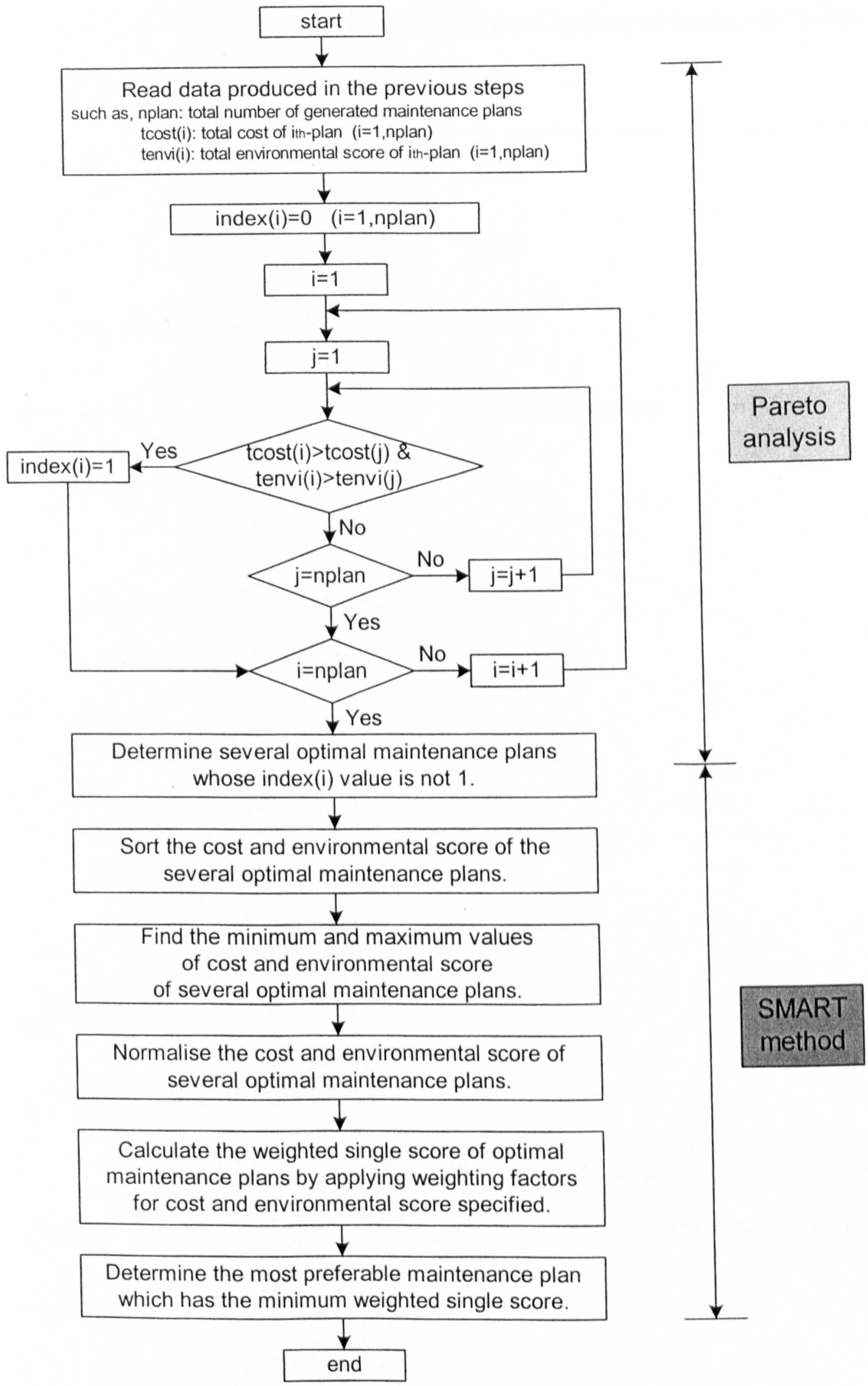


Figure B-6 Flow chart for the calculation of optimal plans based on Pareto analysis and SMART method

Appendix C: Input file structure and description of input variables

C.1 Input file structure

< GENERAL DATA >

ANALYSIS
T=atype R=arange I=niter CP= cp CN= cn

BRIDGE
L=length_brg W=width_brg E=width_lane

TIME
TIME_ZERO=t0 TIME_NOW=t_now TIME_REQ=t_req

DISCOUNT
N=ndiscount B=baseyear
year(1) discount(1)
year(2) discount(2)
---
year(ndiscount) discount(ndiscount)

< MAINTENANCE OPTIONS>

OPTION
N=noption M=gtype

(Case 1: if atype=D and gtype=E)
EFFECTIVE_LIFE
1 L=efflife(1)
2 L=efflife(2)
---
noption L=efflife(noption)

LATEST_OPTION
M=lastoptn

(Case 2: if atype=P and gtype=E)
EFFECTIVE_LIFE
1 L=efflife(1) S=distshp F=factor1,factor2,(factor3),(factor4)
2 L=efflife(2) S=distshp F=factor1,factor2,(factor3),(factor4)
---
noption L=efflife(noption) S=distshp F=factor1,factor2,(factor3),(factor4)

LATEST_OPTION
M=lastoptn

(Case3: if atype=D and gtype=R)
ESSENTIAL
BETA_MAX=b0 BETA_MIN=btarget TIME_I=ti ALPHA=a

PREVENTATIVE
NP=npre

1 GAM=g TEHTA=t TIME_PI=tpi TIME_D0=td TIME_PD=tpd TIME_P=tp
2 GAM=g TEHTA=t TIME_PI=tpi TIME_D0=td TIME_PD=tpd TIME_P=tp

---

npre GAM=g TEHTA=t TIME_PI=tpi TIME_D0=td TIME_PD=tpd TIME_P=tp

INSPECTION
TIME=time_insp BETA=b_insp

(Case 4: if atype=P and gtype=R)
ESSENTIAL

BETA_MAX=b0	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_I=ti	S=distshp	F=factor1,factor2,(factor3),(factor4)
ALPHA=a	S=distshp	F=factor1,factor2,(factor3),(factor4)
BETA_MIN=btarget		

PREVENTATIVE
NP=npre

1		
GAM=g	S=distshp	F=factor1,factor2,(factor3),(factor4)
TEHTA=t	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_PI=tpi	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_D0=td	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_PD=tpd	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_P=tp	S=distshp	F=factor1,factor2,(factor3),(factor4)
2		
GAM=g	S=distshp	F=factor1,factor2,(factor3),(factor4)
TEHTA=t	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_PI=tpi	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_D0=td	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_PD=tpd	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_P=tp	S=distshp	F=factor1,factor2,(factor3),(factor4)
	---	
npre		
GAM=g	S=distshp	F=factor1,factor2,(factor3),(factor4)
TEHTA=t	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_PI=tpi	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_D0=td	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_PD=tpd	S=distshp	F=factor1,factor2,(factor3),(factor4)
TIME_P=tp	S=distshp	F=factor1,factor2,(factor3),(factor4)

INSPECTION
TIME=time_insp BETA=b_insp

< DIRECT IMPACT >

(Case 1: if atype=D)
DCOST

1	C=ducost(1)
2	C=ducost(2)
---	
noption	C=dcost(noption)

DENVI

1	E=duenvi(1)
2	E=duenvi(2)

—
noption **E=duenvi(noption)**

(Case 2: if atype=P)
DCOST
1 **C=ducost(1)** **S=distshp** **F=factor1,factor2,(factor3),(factor4)**
2 **C=ducost(2)** **S=distshp** **F=factor1,factor2,(factor3),(factor4)**
—
noption C=ducost(noption) **S=distshp** **F=factor1,factor2,(factor3),(factor4)**

DENVI
1 **E=duenvi(1)** **S=distshp** **F=factor1,factor2,(factor3),(factor4)**
2 **E=duenvi(2)** **S=distshp** **F=factor1,factor2,(factor3),(factor4)**
—
noption E=duenvi(noption) **S=distshp** **F=factor1,factor2,(factor3),(factor4)**

< INDIRECT IMPACT >

NTC=**num_traffic**

CASE=**index_traffic**
NETWORK
TYPE=**network**

MAIN_ROUTE
CLASS=**road_class** AT=**AT_main** LENGTH=**length_main**

SITE_LENGTH
PRI=**SL_pri** SEC=**SL_sec**

APPROACH_LENGTH
PRI=**AL_pri** SEC=**AL_sec**

WORK_TYPE
PRI=**wtype_pri** SEC=**wtype_sec**

TIDALITY
WDAY=**tidal_weekday** WEND=**tidal_weekend**

FLOW_MAIN
(if atype=D)
AADT=**aadt** OY=**traffic_year**
(if atype=P)
AADT=**aadt** **S=distshp** **F=factor1,factor2,(factor3),(factor4)** OY=**traffic_year**

DIVERSION
LPRI=**ldiv_pri** LSEC=**ldiv_sec** AT=**AT_div**

FLOW_DIVERSION
(if atype=D)
AADT=**aadt_div** OY=**traffic_year_div**
(if atype=P)
AADT=**aadt_div S=distshp F=factor1,factor2,(factor3),(factor4)** OY=**traffic_year_div**

SPEED_DIVERSION

N=nspd_div **V0=v0**
1 **F=flow(1)** **V=v(1)**
2 **F=flow(2)** **V=v(2)**
---
nspd_div **F=flow(nspd_div)** **V=v(nspd_div)**

(Above traffic management data block from CASE=**index_traffic** to SPEED_DIVERSION are repeated to define '**num_traffic**' number of traffic management schemes.)

JOB_WEEK
1 **T=tm1(,tm2)** **WEEK=job_week(1)**
2 **T=tm1(,tm2)** **WEEK=job_week(2)**
---
noption **T=tm1(,tm2)** **WEEK=job_week(noption)**

IENVI
P=petrol_ues **D=diesel_ues**

< WEIGHTING FACTORS >

COST
MFD=mf_dcost **MFI=mf_icost**

ENVI
MFD=mf_denvi **MFI=mf_ienvi**

COMBINE
NWF=nwf
1 **WFC=wf_cost(1)**
2 **WFC=wf_cost(2)**
---
nwf **WFC=wf_cost(nwf)**

C.2 Description of input variables

(1) < GENERAL DATA > Data block

Separator	Variable	Description
ANALYSIS	**atype**	analysis type = D : deterministic analysis = P : probabilistic analysis
	arange	analysis range = D : direct impacts only = B : direct impacts + indirect impacts
	niter	sampling size in the simulation
	cp	relative error used in the convergence check in the probabilistic analysis (%)
	cn	number used in the convergence check to count consecutive convergence situations (integer)
BRIDGE	**length_brg**	length of bridge (m)

	width_brg	total width of bridge superstructure(m)
	width_lane	width of lanes only (m)
TIME	**t0**	time when the bridge was constructed or latest rehabilitation was undertaken (year)
	t_now	present year when the analysis is executed (year)
	t_req	the remaining service life of bridge structure from present year
DISCOUNT	**ndiscount**	number of discount data
	baseyear	reference year to which future costs are discounted
	year(i)	time of i_{th} discount data (year)
	discount(i)	discount rate of i_{th} discount data (%)

(2) < MAINTENANCE OPTIONS > Data block

Separator	**Variable**	**Description**
OPTION	**noption**	number of maintenance options considered
	gtype	maintenance plan generation method = E : based on an effective life concept = R : based on a reliability index approach
EFFECTIVE_LIFE	**i**	order of maintenance option
	efflife(i)	effective life of i_{th} maintenance option
	lastoptn	maintenance option index which was executed at t0 = 0 : no maintenance option was applied at t0 = i (between 1 with noption) : i_{th} maintenance option was applied at t0
	distshp	probabilistic distribution shape = UNI : uniform distribution = TRI : triangular distribution = NOR : normal distribution = LNO : lognormal distribution = LN2 : lognormal 2 distribution = TNO : truncated normal distribution = TLN : truncated lognormal distribution = TL2 : truncated lognormal 2 distribution
	factor1, 2, 3, 4	four factors for defining probabilistic distribution shape
ESSENTIAL	**b0**	initial or maximum reliability index (β_0, β_{max})
	btarget	target or minimum reliability index (β_{min})
	ti	time of damage initiation (t_i)
	a	reliability index deterioration rate (α)
PREVENTATIVE	**npre**	number of preventative maintenance options (here, npre=noption-1)

	g	increase in reliability index immediately after the application of preventative maintenance option (γ)
	t	reduced deterioration rate of reliability index profile during preventative maintenance is effective (θ)
	tpi	first application timing of preventative maintenance option (t_{pi})
	td	time during which the deterioration of reliability index profile is suppressed (t_d)
	tpd	time during which the deterioration rate in reliability index profile is suppressed or reduced (t_{pd})
	tp	time interval of reapplication of preventative maintenance (t_p)
INSPECTION	**time_insp**	time in which bridge inspection is undertaken
	b_insp	reliability index updated based on the inspection result

(3) < DIRECT IMPACT > Data block

Separator	Variable	Description
DCOST	**ducost(i)**	direct cost of i_{th} maintenance option (GBP/m^2)
DENVI	**duenvi(i)**	direct environmental scores of i_{th} maintenance option (point/m^2)

(4) < INDIRECT IMPACT > Data block

Separator	Variable	Description
NTC	**num_traffic**	total number of traffic management schemes to be defined
CASE	**index_traffic**	index for traffic management scheme
NETWORK	**network**	network classification = MWY : motorway = TBU : Build-up Trunk (40 mph speed limit or less) = PBU : Built-up Principal (40 mph speed limit or less) = TNB : Non Built-up Trunk (speed limits above 40 mph) = PNB: Non Built-up Principal (speed limits above 40 mph)
MAIN_ROUTE	**road_class**	road class = 1: Rural single carriageway = 2: Rural all-purpose dual 2 lane carriageway = 3: Rural all-purpose dual 3 or more lane carriageway = 4: Motorway (urban or rural), dual 2 lanes

		= 5: Motorway (urban or rural), dual 3 lanes = 6: Motorway (urban or rural), dual 4 or more lanes
	AT_main	accident type in the absence of site works on the main route = 1: D2 Motorway = 2: D3 Motorway = 3: D4 Motorway = 4: Modern S2 Roads = 5: Modern S2 Roads with hard strip = 6: Modern WS2 Roads = 7: Modern WS2 Roads with hard strip = 9: Other S2 Roads = 10: Modern D2 Roads = 11: Modern D2 Roads with hard strip = 12: Older D2 Roads = 13: Modern D3+ Roads = 14: Modern D3+ Roads with hard strip = 15: Older D3+ Roads
	length_main	length of main route (km)
SITE_LENGTH	**SL_pri**	site length in the primary direction (km)
	SL_sec	site length in the secondary direction (km)
APPROACH_LENGTH	**AL_pri**	approach length in the primary direction (km)
	AL_sec	approach length in the secondary direction (km)
WORK_TYPE	**wtype_pri**	works type in the primary direction = 0: No lanes open in this direction = 1: One lane open in this direction = 2: Two lanes open in this direction = 3: Three lanes open in this direction = 4: Four lanes open in this direction = 5: Five lanes open in this direction = 9: Shuttle working = add 10: if layout features contra-flow working, for example, works type 12 indicates 2 lanes open in contra-flow
	wtype_sec	works type in the secondary direction
TIDALITY	**tf_weekday**	tidality factor on weekday = 1: if primary direction is carrying more traffic in Monday am peak = 2: if secondary direction is carrying more traffic in Monday am peak
	tf_weekend	tidality factor on weekend = 1: if primary direction is carrying more traffic in Friday pm peak = 2: if secondary direction is carrying more traffic in Friday pm peak

FLOW_MAIN	**aadt**	Annual Average Daily Traffic on the main route
	traffic_year	time when AADT on the main route is measured (year)
DIVERSION	**ldiv_pri**	length of diversion route in the primary direction (km)
	ldiv_sec	length of diversion route in the secondary direction (km)
	AT_div	accident type on the diversion route
FLOW_DIVER SION	**aadt_div**	Annual Average Daily Traffic on the diversion route
	traffic_year_ div	time when AADT of diversion route is measured (year)
SPEED_DIVER SION	**nspd_div**	Number of flow/speed pairs used to define speed/flow relationship of diversion route. This does not include a point which define a free speed (v0)
	v0	a free speed in diversion route
	flow(i)	flow in the i_{th} flow/speed pair
	v(i)	speed in the i_{th} flow/speed pair
JOB_WEEK	**tm1(,tm2)**	the index of traffic management scheme(s) related to i_{th} maintenance option (= 0 – num_traffic)
	job_week(i)	the number of weeks required for completing i_{th} maintenance option
IENVI	**petrol_ues**	unit environmental score related to production of 1 litre petroleum
	diesel_ues	unit environmental score related to production of 1 litre diesel

(5) < WEIGHTING FACTORS > Data block

Separator	Variable	Description
COST	**mf_dcost**	weighting factor for direct cost
	mf_icost	weighting factor for indirect cost
ENVI	**mf_denvi**	weighting factor for direct environmental score
	mf_ienvi	weighting factor for indirect environmental score
COMBINE	**nwf**	the number of weighting factors for cost in order to combine cost and environmental score
	wf_cost(i)	weighting factor for cost in the i_{th} combination case

Appendix D: Input file and output for deterministic analysis

D.1 Input file for deterministic analysis

The following input file corresponds to the deterministic analysis case shown in Figure C-3 in this appendix where AADT=60,000, β_0=1.5, β_p=1.3, β_{min}=0.91 and both impacts are considered. Input files for other deterministic analysis cases can be made in a similar way by changing the values of AADT, β_0, β_p and weighting factors for direct and indirect impacts which are underlined in the following data.

```
< GENERAL DATA >

ANALYSIS
T=D     R=B

BRIDGE
L=20.0          W=22.0          E=14.6

TIME
TIME_ZERO=2002       TIME_NOW=2002       TIME_REQ=60

DISCOUNT
N=3    B=2002
2002    3.5
2032    3.0
2077    2.5

< MAINTENANCE OPTIONS>

OPTION
N=4     M=R

ESSENTIAL
BETA_MAX=1.5   BETA_MIN=0.91    TIME_I=3    ALPHA=0.015    ! RE

PREVENTIVE
NP=3
1 GAM=0.0 TEHTA=0.00     TIME_PI=10 TIME_D0=3. TIME_PD=3. TIME_P=10    ! CR
2 GAM=0.0 TEHTA=0.0075 TIME_PI=0 TIME_D0=0. TIME_PD=12. TIME_P=12     ! WF
3 GAM=0.0 TEHTA=0.00     TIME_PI=0 TIME_D0=30. TIME_PD=30. TIME_P=30   ! CP

INSPECTION
TIME=2002    BETA=1.3

< DIRECT IMPACT >

DCOST
```

```
1 C=42.9       ! CR
2 C=27.0       ! WF
3 C=100.0      ! CP
4 C=2106.0     ! RE

DENVI
1 E=1.02       ! CR
2 E=1.84       ! WF
3 E=4.89       ! CP
4 E=61.0       ! RE

< INDIRECT IMPACT >

NTC=1

CASE=1
NETWORK
TYPE=TNB

MAIN_ROUTE
CLASS=2    AT=11    LENGTH=5.0

SITE_LENGTH
PRI=0.2    SEC=0.2

APPROACH_LENGTH
PRI=2.4    SEC=2.4

WORK_TYPE
PRI=11    SEC=1

TIDALITY
WDAY=1 WEND=2

FLOW_MAIN
AADT=60000    OY=2002

DIVERSION
LPRI=7.   LSEC=7.   AT=9

FLOW_DIVERSION
AADT=12000    OY=2002

SPEED_DIVERSION
N=2    V0=78
1    F=900     V=60
2    F=1250    V=45

JOB_WEEK
1    T=1       WEEK=5.5    ! CR
2    T=1       WEEK=4.4    ! WF
3    T=1       WEEK=8.8    ! CP
4    T=1       WEEK=55     ! RE

IENVI
```

P=0.129   D=0.144

< WEIGHTING FACTORS >

COST
<u>MFD=1.0   MFI=1.0</u>

ENVI
<u>MFD=1.0   MFI=1.0</u>

COMBINE
NWF=5
1 WFC=1.0
2 WFC=0.75
3 WFC=0.5
4 WFC=0.25
5 WFC=0.0

D.2 Graphical presentation of deterministic analysis results

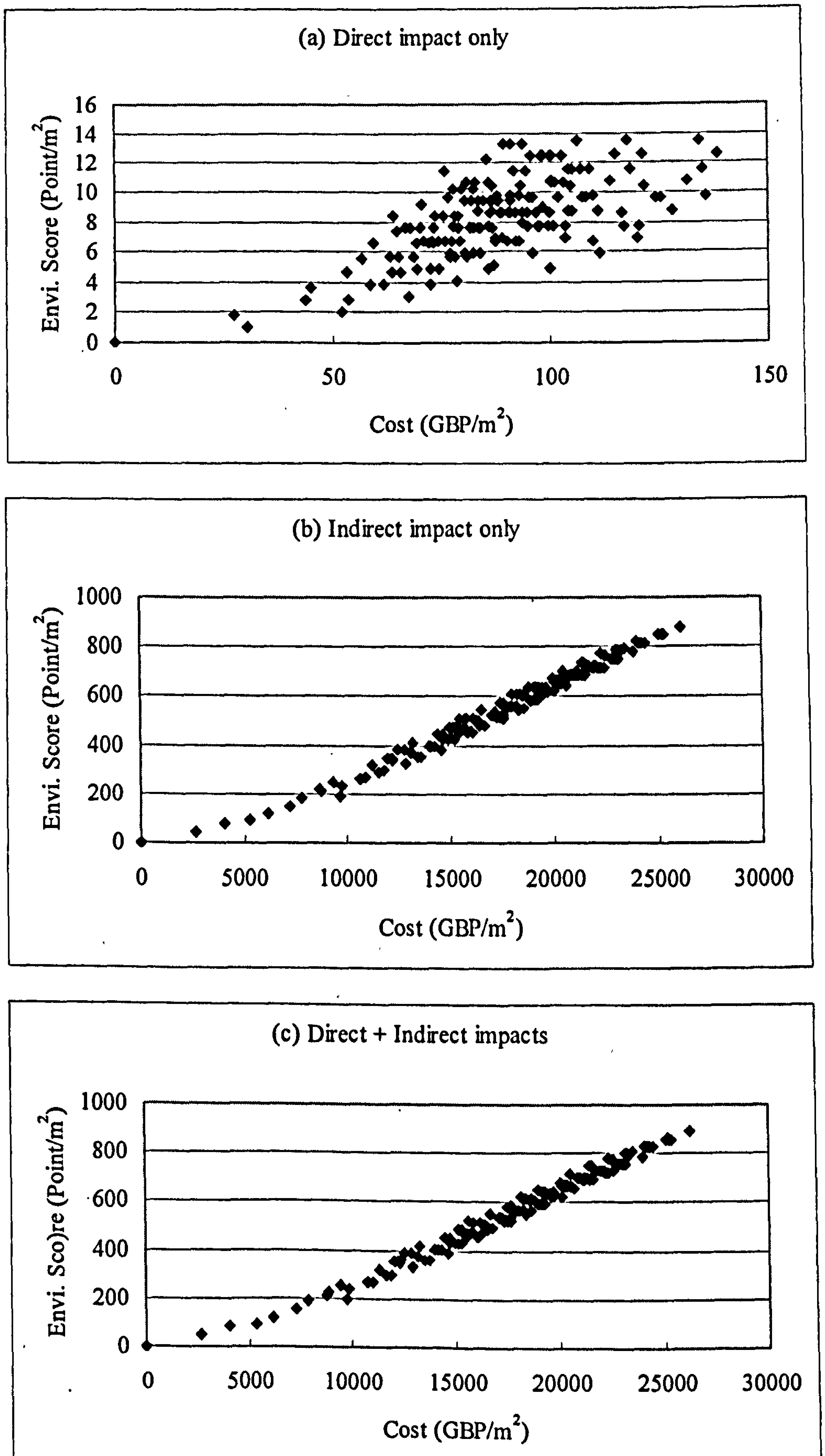


Figure D-1 Distribution of cost and environmental score of maintenance plans.

(When AADT=60,000, C_0=1.8, C_p=1.8, C_{min}=0.91)

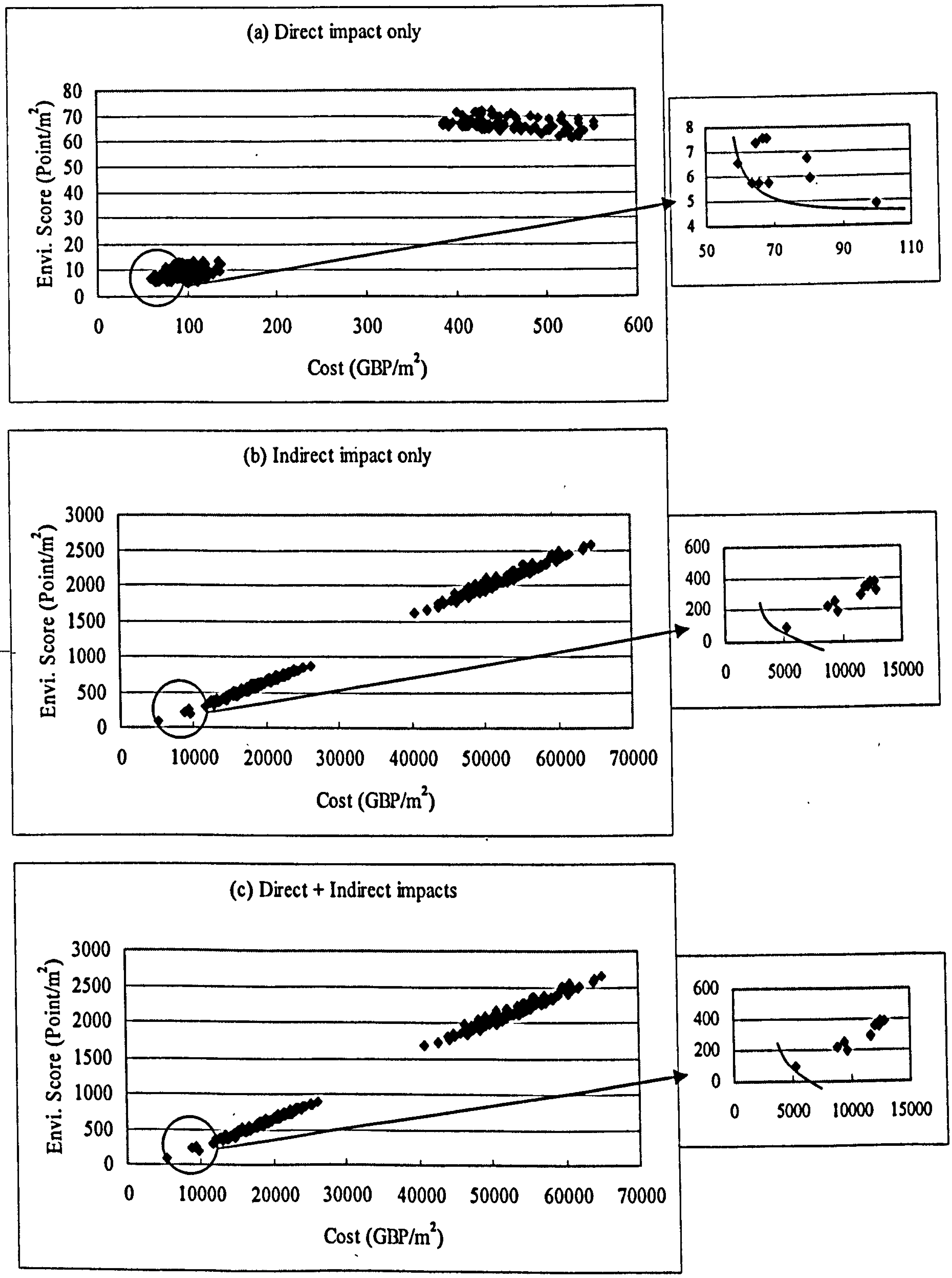


Figure D-2 Distribution of cost and environmental score of maintenance plans.

(When AADT=60,000, C_0=1.5, C_p=1.5, C_{min}=0.91)

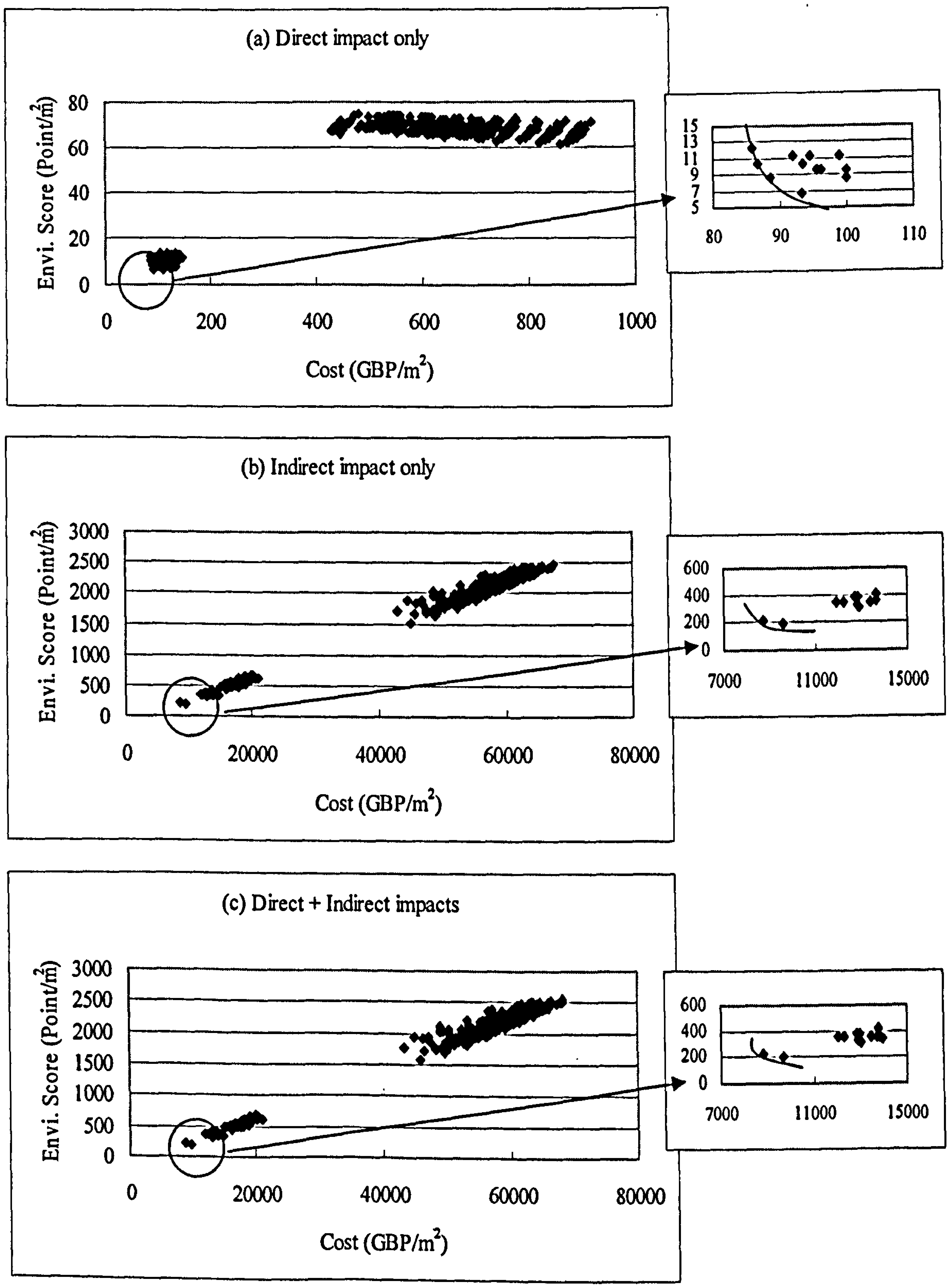


Figure D-3 Distribution of cost and environmental score of maintenance plans.
(When AADT=60,000, C_0=1.5, C_p=1.3, C_{min}=0.91)

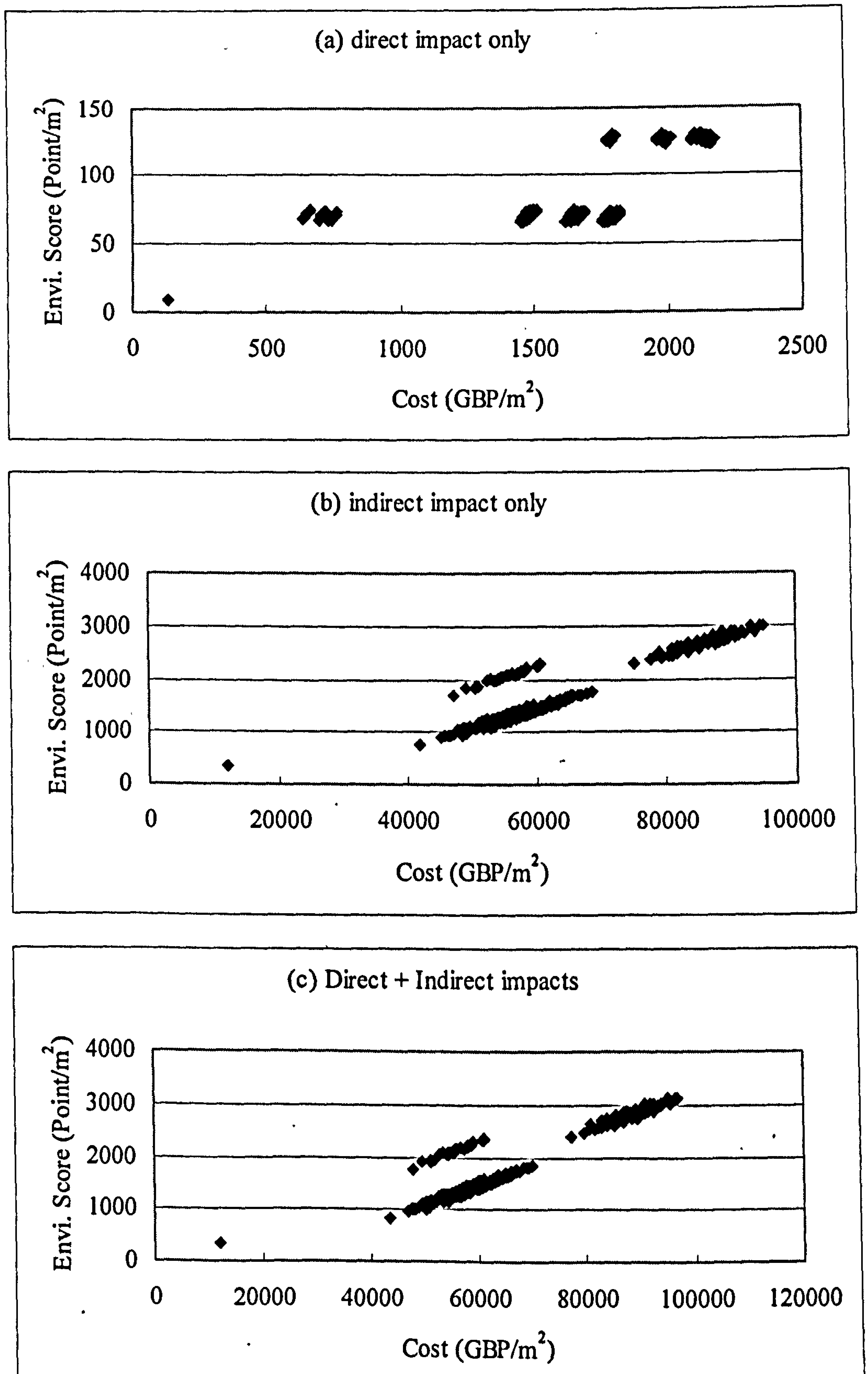


Figure D-4 Distribution of cost and environmental score of maintenance plans.
(When AADT=60,000, C_0=1.5, C_p=1.3, C_{min}=0.91)

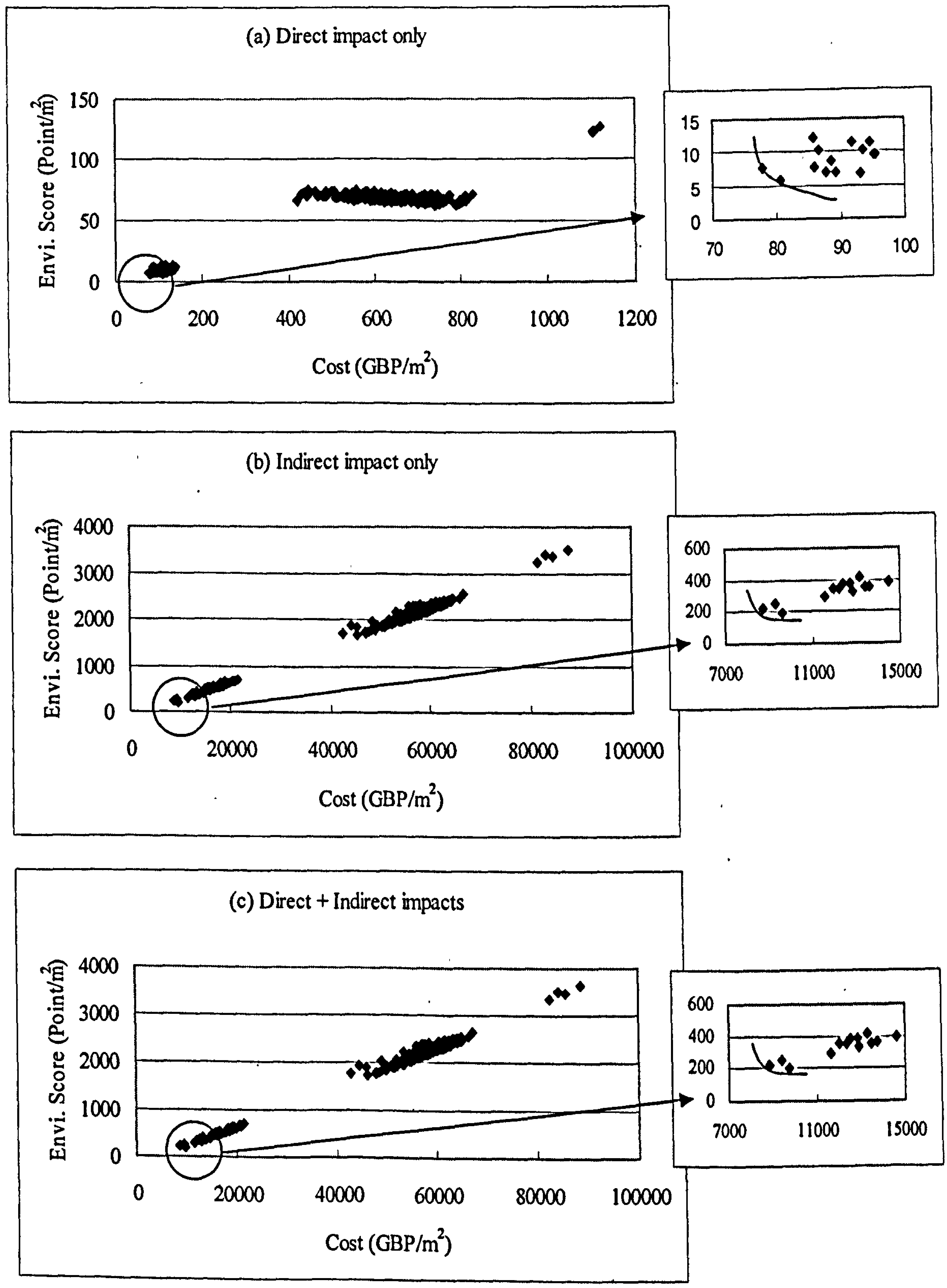


Figure D-5 Distribution of cost and environmental score of maintenance plans.
(When AADT=60,000, C_0=1.3, C_p=1.3, C_{min}=0.91)

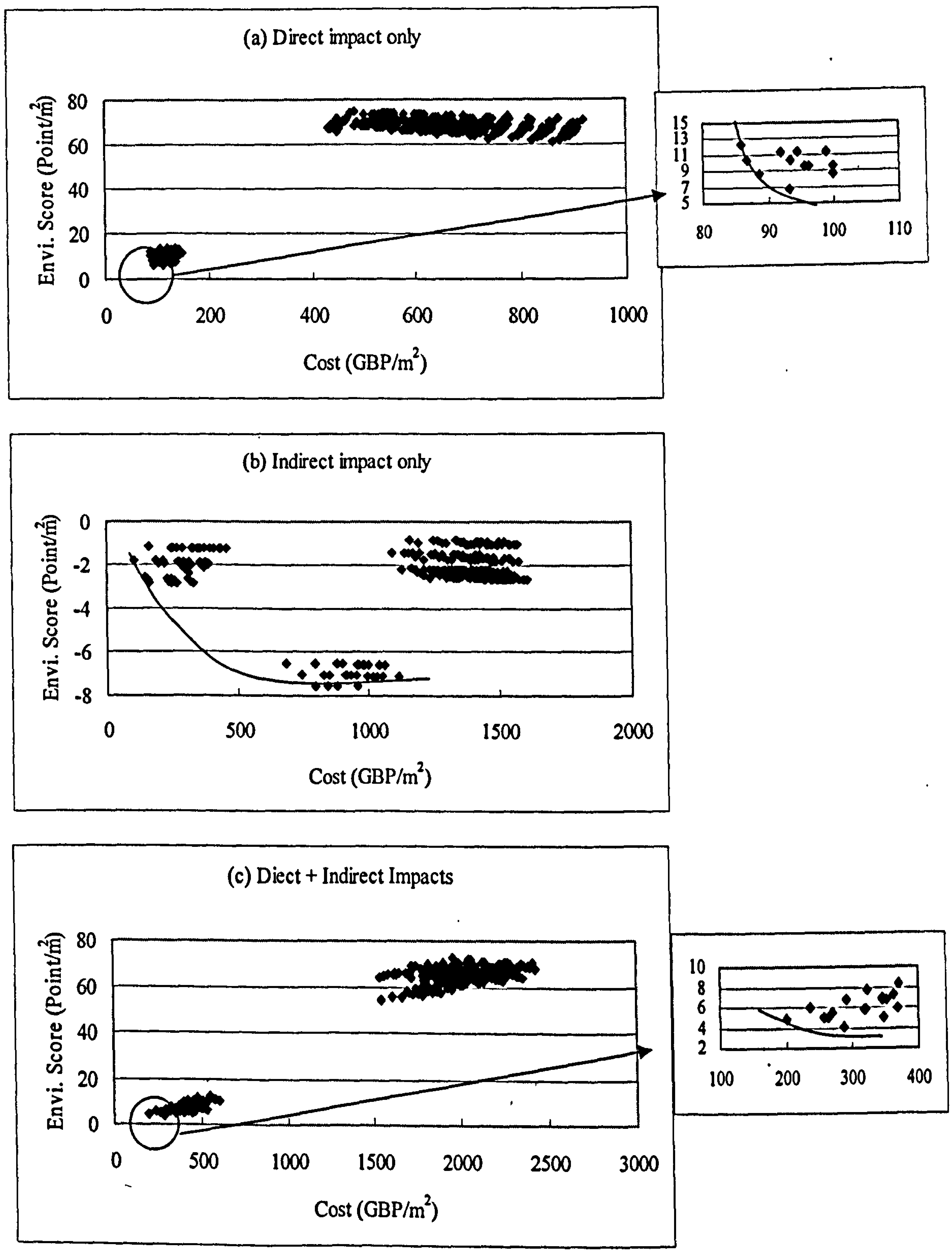


Figure D-6 Distribution of cost and environmental score of maintenance plans.

(When AADT=20,000, C_0=1.5, C_p=1.3, C_{min}=0.91)

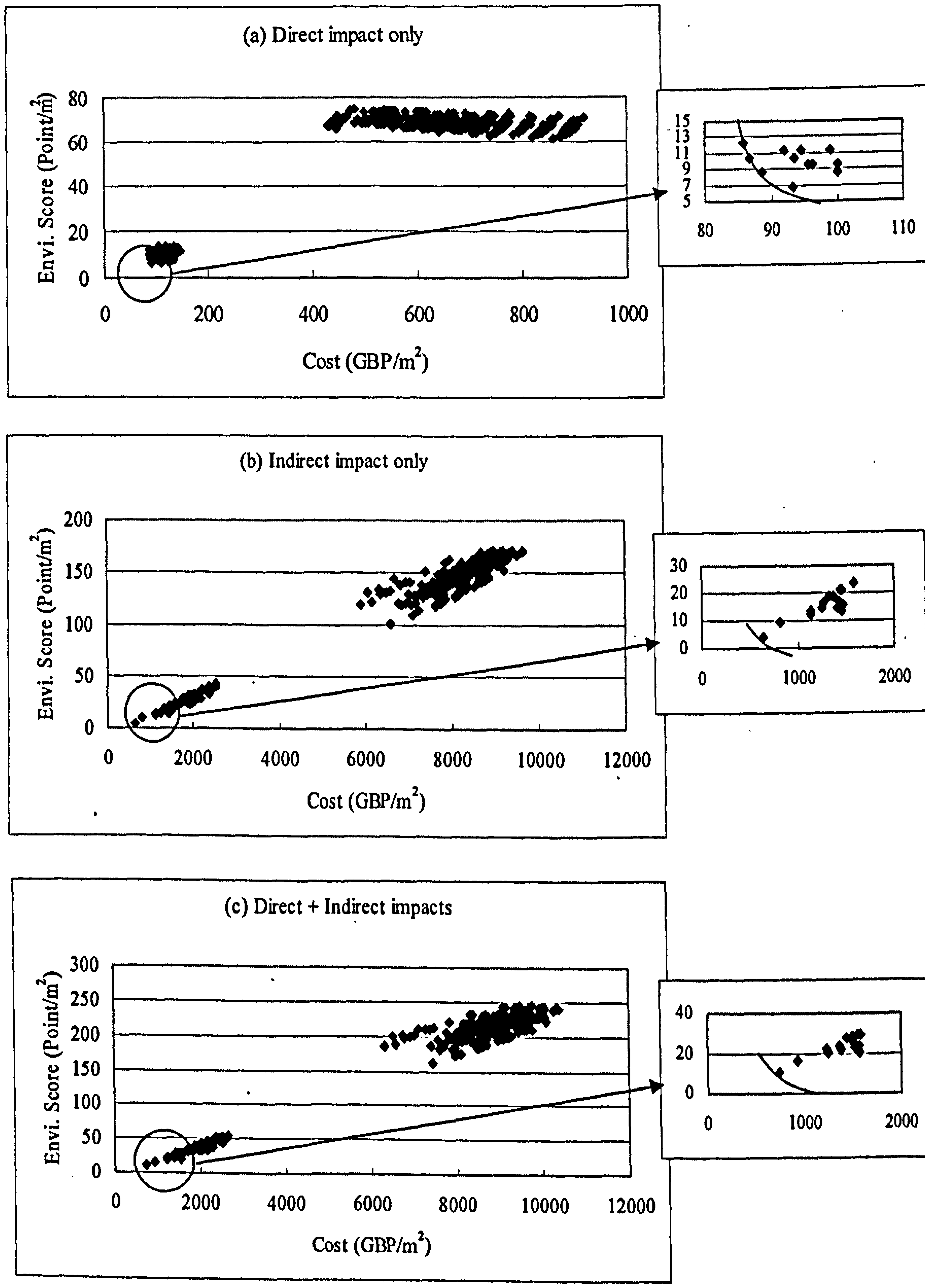


Figure D-7 Distribution of cost and environmental score of maintenance plans.
(When AADT=30,000, C_0=1.5, C_p=1.3, C_{min}=0.91)

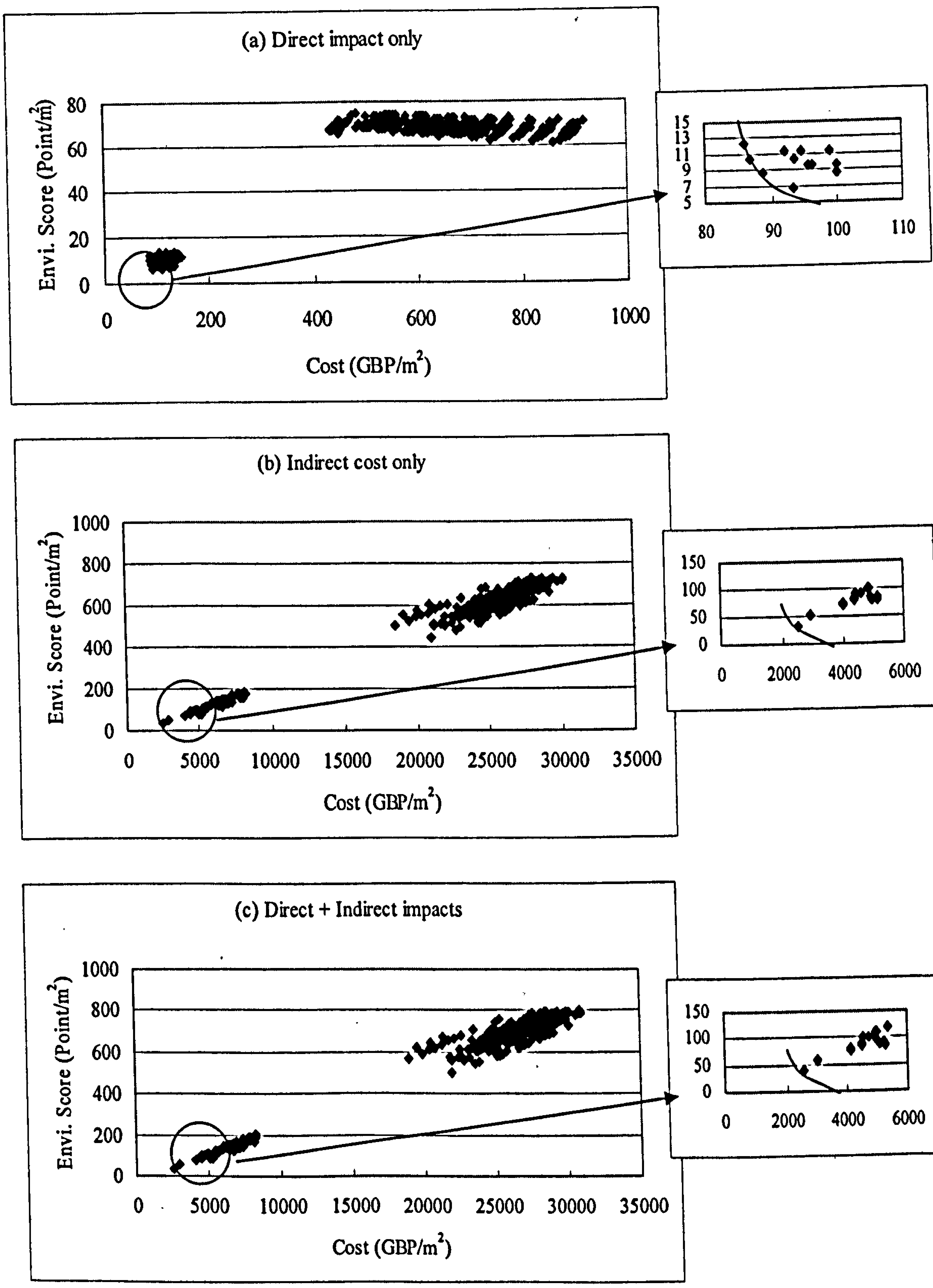


Figure D-8 Distribution of cost and environmental score of maintenance plans.
(When AADT=40,000, C_0=1.5, C_p=1.3, C_{min}=0.91)

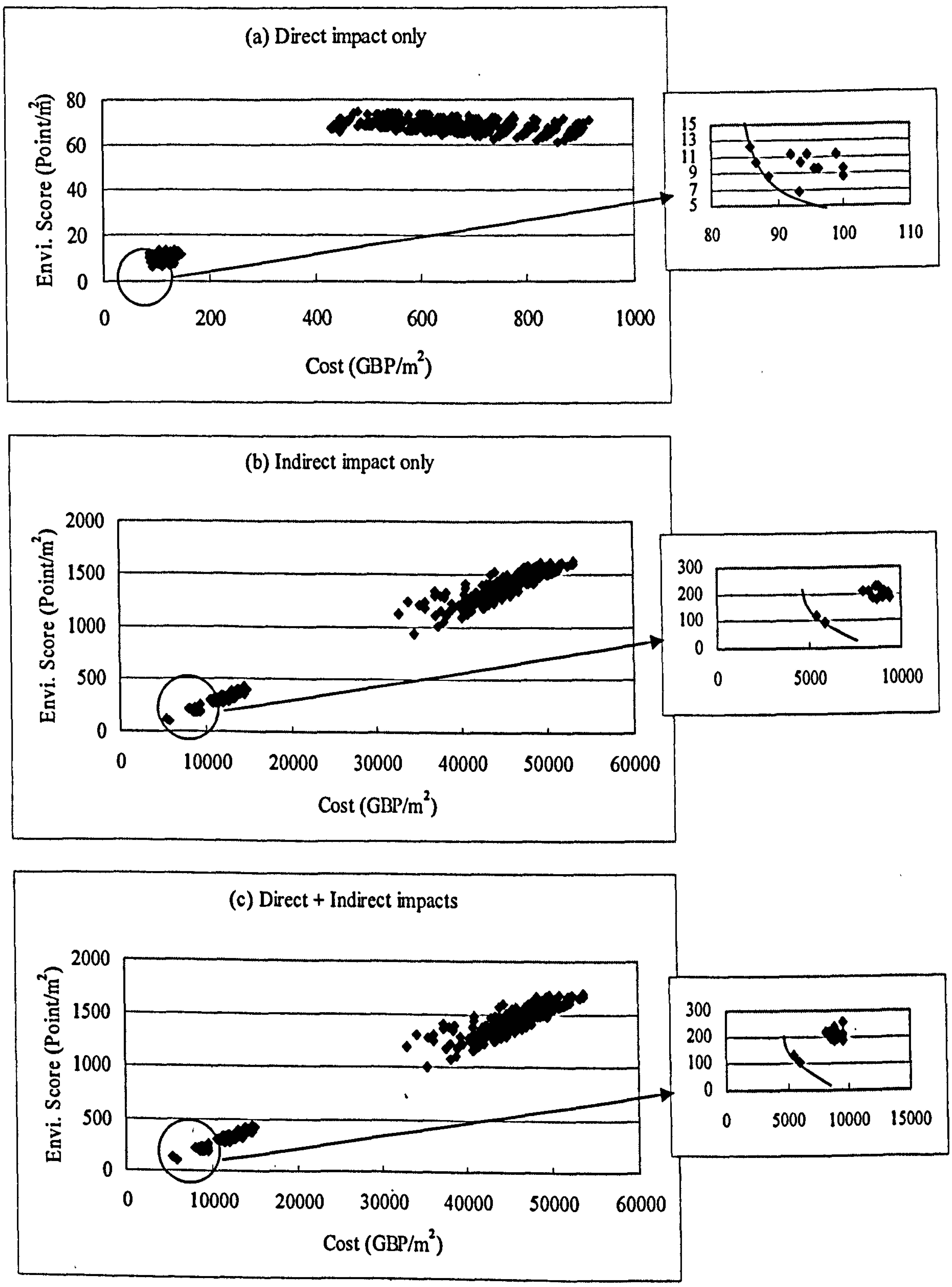


Figure D-9 Distribution of cost and environmental score of maintenance plans.

(When AADT=50,000, C_0=1.5, C_p=1.3, C_{min}=0.91)

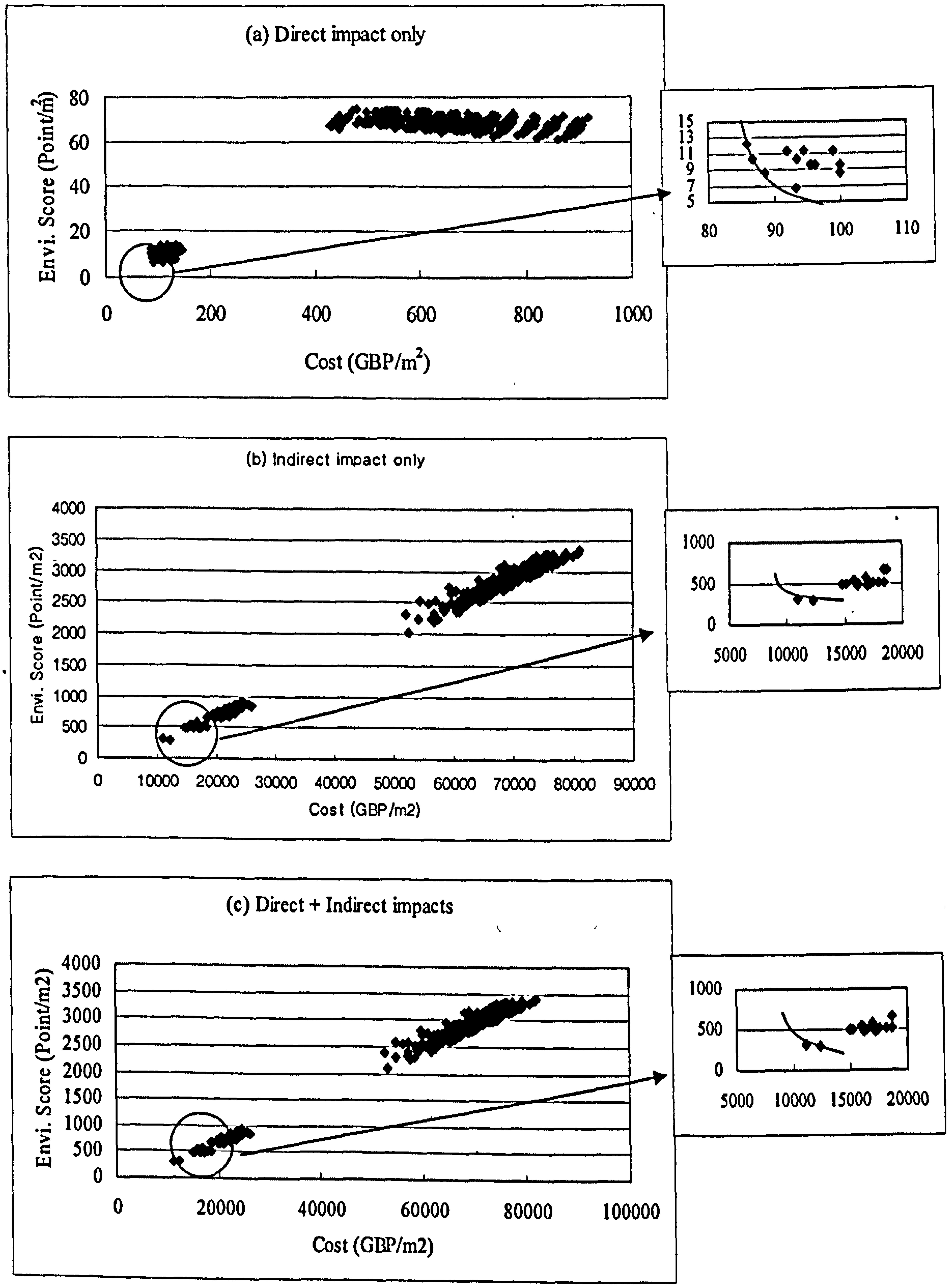


Figure D-10 Distribution of cost and environmental score of maintenance plans.

(When AADT=70,000, C_0=1.5, C_p=1.3, C_{min}=0.91)

D.3 An example for verifying the credibility of the computer code developed in calculating direct impacts of a maintenance plan

In order to show the process of generating a maintenance plan as well as to verify the accuracy of the values of direct cost and environmental score calculated by a computer code developed in this study, one of the optimal maintenance plans in case of AADT=60,000, C_0=1.5, C_p=1.5, C_{min}=0.91 in Table 7.4, i.e. (92) CR-WP-WP-CR-DN, is analysed by hand here.

1) Application timing of maintenance plans and the change of performance profile

The application timing of maintenance options and corresponding change of performance profile of the plan 'CR-WP-WP-CR-DN' is shown in Figure C-11 and Table C-1 below.

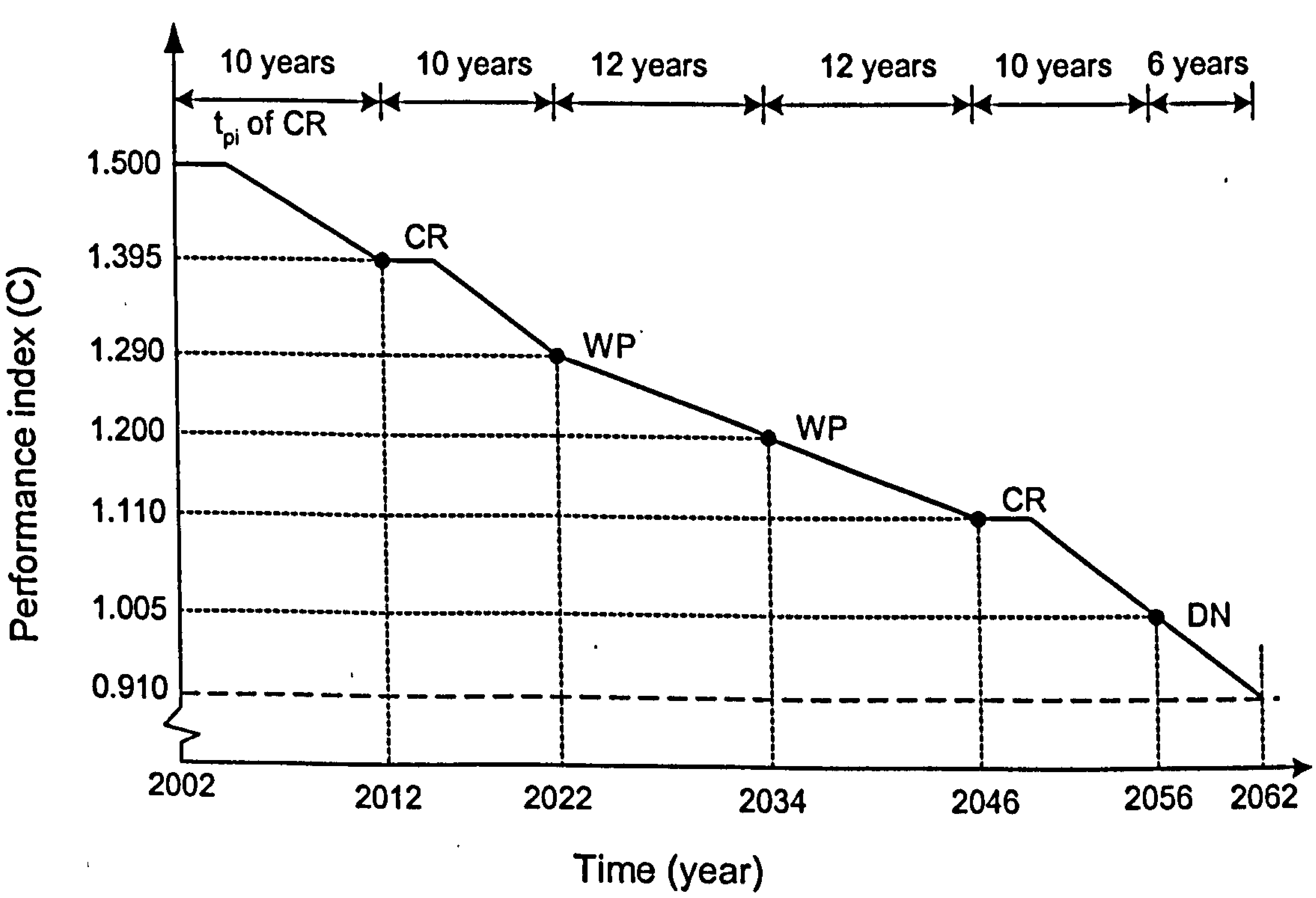


Figure D-11 Performance profile of a maintenance plan 'CR-WP-WP-CR-DN'

Table D-1 Maintenance timing and corresponding change of performance profile

Order	Maintenance Method	Time change		Performance change	
		T_{iend}	T_{jend}	C_{iend}	C_{jend}
1	CR	2012	2022	1.395	1.290
2	WP	2022	2034	1.290	1.200
3	WP	2034	2046	1.200	1.110
4	CR	2046	2056	1.110	1.005
5	DN	2056	2062	1.005	0.910

2) Calculation of direct cost and environmental score

The direct cost and environmental score of a maintenance plan 'CR-WP-WP-CR-DN' calculated by hand is given in Table C-2 below. The direct cost and environmental score are same with those in Table 7.4 which were produced by the computer code developed in this study.

Table D-2 Direct cost and environmental score of a plan 'CR-WP-WP-CR-DN'

Order & Method		Application Timing	Direct cost			Direct Envi. Score
			Before discount	Discount factor	After Discount	
1	CR	2012	42.9	$1/(1+0.035)^{10}=0.709$	30.4	1.02
2	WP	2022	27.0	$1/(1+0.035)^{20}=0.503$	13.6	1.84
3	WP	2034	27.0	$1/((1+0.035)^{30}(1+0.03)^{2})=0.336$	9.10	1.84
4	CR	2046	42.9	$1/((1+0.035)^{30}(1+0.03)^{14})=0.236$	10.1	1.02
5	DN	2056	0.00	$1/((1+0.035)^{30}(1+0.03)^{24})=0.175$	0.00	0.00
				SUM	63.2	5.72

Appendix E: Input file for probabilistic analysis

E.1 Input file for probabilistic analysis (CASE 1)

```
< GENERAL DATA >

ANALYSIS
T=P     I=1000     R=D     CP=0.1      CN=15

BRIDGE
L=20.0     W=22.0     E=14.6

TIME
TIME_ZERO=2002.   TIME_NOW=2002.   TIME_REQ=60

DISCOUNT
N=2    B=2002
2002       3.5
2032       3.0

< MAINTENANCE OPTIONS>

OPTION
N=4        M=R

ESSENTIAL
BETA_MAX=1.5    S=UNI     F=1.5,1.5
TIME_I=3.0      S=UNI     F=3.0,3.0
ALPHA=0.015     S=UNI     F=0.015,0.015
BETA_MIN=0.91

PREVENTIVE
NP=3
1
GAM=0.0           S=UNI     F=0.0,0.0
TEHTA=0.00        S=UNI     F=0.0,0.0
TIME_PI=10        S=UNI     F=10.0,10.0
TIME_D0=0.        S=UNI     F=0.0,0.0
TIME_PD=3.        S=UNI     F=3.0,3.0
TIME_P=10         S=UNI     F=10.0,10.0
2
GAM=0.0           S=UNI     F=0.0,0.0
TEHTA=0.0075      S=UNI     F=0.0075,0.0075
TIME_PI=0         S=UNI     F=0.0,0.0
TIME_D0=0         S=UNI     F=0.0,0.0
TIME_PD=12.       S=UNI     F=12.0,12.0
TIME_P=12         S=UNI     F=12.0,12.0
3
GAM=0.0           S=UNI     F=0.0,0.0
TEHTA=0.0         S=UNI     F=0.0,0.0
TIME_PI=0         S=UNI     F=0.0,0.0
TIME_D0=30        S=UNI     F=30.0,30.0
TIME_PD=30        S=UNI     F=30.0,30.0
```

```
TIME_P=30        S=UNI      F=30.0,30.0

INSPECTION
TIME=2000     BETA=0.0

< DIRECT IMPACT >

DCOST
1 C=42.9        S=TRI     F=21.45,42.9,64.35      ! Concrete repair
2 C=27.0        S=TRI     F=13.5,27,40.5          ! Waterproofing
3 C=100.0       S=TRI     F=50.0,100.0,150        ! Cathodic protection
4 C=2106        S=TRI     F=1053,2106,3159        ! Replacement of element

DENVI
1 E=1.02        S=TRI     F=0.51,1.02,1.53        ! Concrete repair
2 E=1.84        S=TRI     F=0.92,1.84,2.76        ! Waterproofing
3 E=4.89        S=TRI     F=2.445,4.89,7.335      ! Cathodic protection
4 E=61.0        S=TRI     F=30.5,61,91.5          ! Replacement of element

< WEIGHTING FACTORS >

COST
MFD=1.0     MFI=0.0

ENVI
MFD=1.0     MFI=0.0

COMBINE
NWF=5
1 WFC=1.0
2 WFC=0.75
3 WFC=0.5
4 WFC=0.25
5 WFC=0.0
```

E.2 Input file for probabilistic analysis (CASE 2)

```
< GENERAL DATA >

ANALYSIS
T=P      I=1000     R=B     CP=0.1      CN=15

BRIDGE
L=20.0           W=22.0          E=14.6

TIME
TIME_ZERO=2002.  TIME_NOW=2002.  TIME_REQ=60

DISCOUNT
N=2    B=2002
2002    3.5
2032    3.0
```

```
< MAINTENANCE OPTIONS>

OPTION
N=4     M=R

ESSENTIAL
BETA_MAX=1.5        S=UNI    F=1.5,1.5
TIME_I=3.0          S=UNI    F=3.0,3.0
ALPHA=0.015         S=UNI    F=0.015,0.015
BETA_MIN=0.91

PREVENTIVE
NP=3
1
GAM=0.0             S=UNI    F=0.0,0.0
TEHTA=0.00          S=UNI    F=0.0,0.0
TIME_PI=10          S=UNI    F=10.0,10.0
TIME_D0=0.          S=UNI    F=0.0,0.0
TIME_PD=3.          S=UNI    F=3.0,3.0
TIME_P=10           S=UNI    F=10.0,10.0
2
GAM=0.0             S=UNI    F=0.0,0.0
TEHTA=0.0075        S=UNI    F=0.0075,0.0075
TIME_PI=0           S=UNI    F=0.0,0.0
TIME_D0=0           S=UNI    F=0.0,0.0
TIME_PD=12.         S=UNI    F=12.0,12.0
TIME_P=12           S=UNI    F=12.0,12.0
3
GAM=0.0             S=UNI    F=0.0,0.0
TEHTA=0.0           S=UNI    F=0.0,0.0
TIME_PI=0           S=UNI    F=0.0,0.0
TIME_D0=30          S=UNI    F=30.0,30.0
TIME_PD=30          S=UNI    F=30.0,30.0
TIME_P=30           S=UNI    F=30.0,30.0

INSPECTION
TIME=2000    BETA=0.0

< DIRECT IMPACT >

DCOST
1 C=42.9     S=TRI    F=21.45,42.9,64.35     ! Concrete repair
2 C=27.0     S=TRI    F=13.5,27,40.5         ! Waterproofing
3 C=100.0    S=TRI    F=50.0,100.0,150       ! Cathodic protection
4 C=2106     S=TRI    F=1053,2106,3159       ! Replacement of element

DENVI
1 E=1.02     S=TRI    F=0.51,1.02,1.53       ! Concrete repair
2 E=1.84     S=TRI    F=0.92,1.84,2.76       ! Waterproofing
3 E=4.89     S=TRI    F=2.445,4.89,7.335     ! Cathodic protection
4 E=61.0     S=TRI    F=30.5,61,91.5         ! Replacement of element

< INDIRECT IMPACT >
```

```
NTC=1

CASE=1
NETWORK
TYPE=TNB

MAIN_ROUTE
CLASS=2     AT=11     LENGTH=5.0

SITE_LENGTH
PRI=0.2     SEC=0.2

APPROACH_LENGTH
PRI=2.4     SEC=2.4

WORK_TYPE
PRI=11     SEC=1

TIDALITY
WDAY=1 WEND=2

FLOW_MAIN
AADT=50000     S=TRI     F=25000,50000,75000   OY=2002

DIVERSION
LPRI=7.0     LSEC=7.0     AT=9

FLOW_DIVERSION
AADT=12000     S=TRI F=6000,12000,18000     OY=2002

SPEED_DIVERSION
N=2    V0=78
1         F=900       V=60
2         F=1250      V=45

JOB_WEEK
1   T=1       WEEK=5.5        ! Concrete repair
2   T=1       WEEK=4.4        ! Waterproofing
3   T=1       WEEK=8.8        ! Cathodic protection
4   T=1       WEEK=55         ! Replacement of element

IENVI
P=0.129     D=0.144

< WEIGHTING FACTORS >

COST
MFD=1.0     MFI=1.0

ENVI
MFD=1.0     MFI=1.0

COMBINE
NWF=5
1 WFC=1.0
```

```
2 WFC=0.75
3 WFC=0.5
4 WFC=0.25
5 WFC=0.0
```

E.3 Input file for probabilistic analysis (CASE 3)

```
< GENERAL DATA >

ANALYSIS
T=P     I=1000     R=D     CP=0.1     CN=15

BRIDGE
L=20.0     W=22.0     E=14.6

TIME
TIME_ZERO=2002.     TIME_NOW=2002.     TIME_REQ=60

DISCOUNT
N=2     B=2002
2002     3.5
2032     3.0

< MAINTENANCE OPTIONS>

OPTION
N=4     M=R

ESSENTIAL
BETA_MAX=1.5        S=TRI     F=1.2,1.5,1.8
TIME_I=3.0          S=TRI     F=1.5,3.0,4.5
ALPHA=0.015         S=TRI     F=0.0075,0.015,0.0225
BETA_MIN=0.91

PREVENTIVE
NP=3
1
GAM=0.0             S=UNI     F=0.0,0.0
TEHTA=0.00          S=UNI     F=0.0,0.0
TIME_PI=10          S=TRI     F=5.0,10.0,15.0
TIME_D0=0.          S=UNI     F=0.0,0.0
TIME_PD=3.          S=TRI     F=1.5,3.0,4.5
TIME_P=10           S=TRI     F=5.0,10.0,15.0
2
GAM=0.0             S=UNI     F=0.0,0.0
TEHTA=0.0075        S=TRI     F=0.00375,0.0075,0.01125
TIME_PI=0           S=UNI     F=0.0,0.0
TIME_D0=0           S=UNI     F=0.0,0.0
TIME_PD=12.         S=TRI     F=6.0,12.0,18.0
TIME_P=12           S=TRI     F=6.0,12.0,18.0
3
GAM=0.0             S=UNI     F=0.0,0.0
TEHTA=0.0           S=UNI     F=0.0,0.0
```

```
TIME_PI=0          S=UNI        F=0.0,0.0
TIME_D0=30         S=TRI        F=15.0,30.0,45.0
TIME_PD=30         S=TRI        F=15.0,30.0,45.0
TIME_P=30          S=TRI        F=15.0,30.0,45.0

INSPECTION
TIME=2000    BETA=0.0

< DIRECT IMPACT >

DCOST
1 C=42.9       S=TRI       F=21.45,42.9,64.35       ! Concrete repair
2 C=27.0       S=TRI       F=13.5,27,40.5           ! Waterproofing
3 C=100.0      S=TRI       F=50.0,100.0,150         ! Cathodic protection
4 C=2106       S=TRI       F=1053,2106,3159         ! Replacement of element

DENVI
1 E=1.02       S=TRI       F=0.51,1.02,1.53         ! Concrete repair
2 E=1.84       S=TRI       F=0.92,1.84,2.76         ! Waterproofing
3 E=4.89       S=TRI       F=2.445,4.89,7.335       ! Cathodic protection
4 E=61.0       S=TRI       F=30.5,61,91.5           ! Replacement of element

< WEIGHTING FACTORS >

COST
MFD=1.0    MFI=0.0

ENVI
MFD=1.0    MFI=0.0

COMBINE
NWF=5
1 WFC=1.0
2 WFC=0.75
3 WFC=0.5
4 WFC=0.25
5 WFC=0.0
```

E.4 Input file for probabilistic analysis (CASE 4)

```
< GENERAL DATA >

ANALYSIS
T=P    I=1500    R=B    CP=0.1    CN=15

BRIDGE
L=20.0    W=22.0    E=14.6

TIME
TIME_ZERO=2002.    TIME_NOW=2002.    TIME_REQ=60

DISCOUNT
```

```
N=2    B=2002
2002     3.5
2032     3.0

< MAINTENANCE OPTIONS>

OPTION
N=4      M=R

ESSENTIAL
BETA_MAX=1.5          S=TRI          F=1.2,1.5,1.8
TIME_I=3.0            S=TRI          F=1.5,3.0,4.5
ALPHA=0.015           S=TRI          F=0.0075,0.015,0.0225
BETA_MIN=0.91

PREVENTIVE
NP=3
1
GAM=0.0               S=UNI          F=0.0,0.0
TEHTA=0.00            S=UNI          F=0.0,0.0
TIME_PI=10            S=TRI          F=5.0,10.0,15.0
TIME_D0=0.            S=UNI          F=0.0,0.0
TIME_PD=3.            S=TRI          F=1.5,3.0,4.5
TIME_P=10             S=TRI          F=5.0,10.0,15.0
2
GAM=0.0               S=UNI          F=0.0,0.0
TEHTA=0.0075          S=TRI          F=0.00375,0.0075,0.01125
TIME_PI=0             S=UNI          F=0.0,0.0
TIME_D0=0             S=UNI          F=0.0,0.0
TIME_PD=12.           S=TRI          F=6.0,12.0,18.0
TIME_P=12             S=TRI          F=6.0,12.0,18.0
3
GAM=0.0               S=UNI          F=0.0,0.0
TEHTA=0.0             S=UNI          F=0.0,0.0
TIME_PI=0             S=UNI          F=0.0,0.0
TIME_D0=30            S=TRI          F=15.0,30.0,45.0
TIME_PD=30            S=TRI          F=15.0,30.0,45.0
TIME_P=30             S=TRI          F=15.0,30.0,45.0

INSPECTION
TIME=2000    BETA=0.0

< DIRECT IMPACT >

DCOST
1 C=42.9        S=TRI        F=21.45,42.9,64.35        ! Concrete repair
2 C=27.0        S=TRI        F=13.5,27,40.5            ! Waterproofing
3 C=100.0       S=TRI        F=50.0,100.0,150          ! Cathodic protection
4 C=2106        S=TRI        F=1053,2106,3159          ! Replacement of element

DENVI
1 E=1.02        S=TRI        F=0.51,1.02,1.53          ! Concrete repair
2 E=1.84        S=TRI        F=0.92,1.84,2.76          ! Waterproofing
3 E=4.89        S=TRI        F=2.445,4.89,7.335        ! Cathodic protection
4 E=61.0        S=TRI        F=30.5,61,91.5            ! Replacement of element
```

```
< INDIRECT IMPACT >

NTC=1

CASE=1
NETWORK
TYPE=TNB

MAIN_ROUTE
CLASS=2      AT=11       LENGTH=5.0

SITE_LENGTH
PRI=0.2      SEC=0.2

APPROACH_LENGTH
PRI=2.4      SEC=2.4

WORK_TYPE
PRI=11       SEC=1

TIDALITY
WDAY=1 WEND=2

FLOW_MAIN
AADT=50000    S=TRI     F=25000,50000,75000     OY=2002

DIVERSION
LPRI=7.0      LSEC=7.0      AT=9

FLOW_DIVERSION
AADT=12000    S=TRI     F=6000,12000,18000     OY=2002

SPEED_DIVERSION
N=2     V0=78
1         F=900       V=60
2         F=1250      V=45

JOB_WEEK
1    T=1        WEEK=5.5        ! Concrete repair
2    T=1        WEEK=4.4        ! Waterproofing
3    T=1        WEEK=8.8        ! Cathodic protection
4    T=1        WEEK=55         ! Replacement of element

IENVI
P=0.129    D=0.144

< WEIGHTING FACTORS >

COST
MFD=1.0    MFI=1.0

ENVI
MFD=1.0    MFI=1.0
```

COMBINE
NWF=5
1 WFC=1.0
2 WFC=0.75
3 WFC=0.5
4 WFC=0.25
5 WFC=0.0