THE SUSTAINABILITY ASSESSMENT OF PROJECTS: AN ARTIFICIAL INTELLIGENCE APPROACH, WITH APPLICATION TO TASMANIA.

by

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Submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy

University of Tasmania
Faculty of Science and Engineering
School of Engineering (Ltn)

April 1999

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This thesis is dedicated with much love to my wife, Tisha.

Signed Statements

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Abstract

This thesis develops and presents a practical method of assessing the sustainability impact of projects. The research has been motivated by the fact that sustainability is an accepted goal of resource management and planning legislation, and yet we have few tools with which to quantitatively assess sustainability impacts.

The history of the sustainability imperative is reviewed, and it is proposed that sustainability be considered in terms of three themes which match the way in which most planners think about sustainability issues, and commission specialist studies:

1. *Biodiversity.* Biological diversity and integrity.
2. *Socio-economic.* Well being and equity within and between generations.
3. *Physical environmental.* Local, regional and global environmental quality.

A sustainability assessment method is developed, whereby project impacts are measured using indicators of the sustainability issues associated with the project. This takes advantage of the indicator sets being developed by the Local Agenda 21 initiative, and by the State of the Environment reporting process. Ways are examined to aggregate indicators into indices, using both traditional approaches and expert systems. Fuzzy rule systems and neural networks are shown to offer powerful, natural alternatives to traditional aggregation methods, and case studies are presented which use these tools to aggregate information relating to roadside vegetation quality, algal blooms, urban air quality, and sewage treatment plant performance.

A traditional modelling approach to predicting indicator changes would solve (numerically integrate) the differential equations governing the interactions between the indicators, computing interaction terms at each time step. However, in this instance the equations are unknown, and the inputs are often known only semi-quantitatively. A modelling approach based on a fuzzy rule system is developed that overcomes these barriers, in which indicator changes due to interactions between indicators are computed iteratively. The model is applied to a number of basic situations, and approaches to driving the model are discussed. Model performance and sensitivity tests are carried out that demonstrate the behaviour of the model to be reasonable, and an illustrative application is presented.

The sustainability assessment method is further validated by case studies in mining, forestry and road transport planning. The model predictions compare well to expectations, although rigorous test data are not yet available, and the method is shown to be an effective tool for screening projects, particularly when used to compare project options. It can be used to improve the design of baseline studies, to design appropriate monitoring programs, and to examine the need for application of the precautionary principle.

The use of multi-criteria decision-making methods and genetic algorithms to select and optimise a preferred project option is explored, and illustrated by application to a proposed road upgrade project. The thesis concludes by discussing follow-on areas of research, and approaches to improving the assessment method.

Acknowledgements

Somewhere a doctoral thesis may exist which was produced without the benefit of helpful suggestions from numerous people. Not this one ! I am very grateful to my wife, family, and friends for their support, and many thanks also to the following people:

- My supervisors and advisors: Associate Professor Peter Doe and Dr Michael Negnevitsky (University of Tasmania), and Dr Barry Tapp (UNITEC, Auckland).

- The Tasmanian Department of Transport, who sponsored my research, and contributed to it many ways. Special thanks to Brian Flakelar, Andrew van Emmerik, Ian Gibbs, Jed Gillian, John Pauley, Karin Wheeler and Tony Wilson.

- Dr John Hunter (CSIRO), for advice on modelling sustainability indicator changes; and Professor Bill Budd (Antarctic CRC), for his review of the modelling approach.

- The CSIRO Division of Marine Research, particularly Dr Sue Blackburn, Dr Ed Butler, Dr Jim Mansbridge and Naomi Parker.

- Forestry Tasmania and North Forests Burnie. Special thanks to David Bowden, Penny Douglas, Malcolm Hatcher, Jeremy Wilson and Penny Wells.

- Launceston City Council, particularly Paula Garwood and Bill Piesse.

- The Bureau of Meteorology, particularly Doug Shepherd and Ian Barnes-Keoghan.

- Copper Mines of Tasmania, particularly Dr Alan Robertson.

- Numerous environmental consultants. Special thanks to Tom Griffiths, Andrew North, Cathy Searle, Jim Stephens, Richard Stoklosa, and Dr Bill Wilson.

- Many librarians. Special thanks to Jill Wells (University of Tasmania), Dennis Abbott (CSIRO), Judy Jensen (Dept. of Transport), and Fiona Preston (Dept. of Environment).

- My students at the University of Tasmania, and at TAFE, for reminding me that there often many ways to approach a problem.

Supporting Publications

The author has been involved in over 200 environmental engineering projects in Canada and Australia. In 1994, he established Environmental Dynamics, a consulting practice in Hobart, and in 1995 he received an Engineering Excellence Award from the Institution of Engineers, Australia (Tasmania Division). The research for this thesis was carried out from 1996 to 1999, and is supported by the following publications.

Chapter of Text

Carter, S.J.B. and J.R. Pauley [1996]. *Transport Chapter* In *State of the Environment Tasmania.* Sustainable Development Advisory Council, Department of Environment & Land Management, Tasmania, December 1996.

Conference Papers

Carter, S.J.B. and M. Negnevitsky [1999]. *Aggregation of Sustainability Indicators: Traditional and Expert System Methods.* Draft paper submitted to the Australasian Environmental Engineering Conference, Auckland, July 1999. Abstract accepted.

Carter, S.J.B., E.J. Gillian, and B. Tapp [1998]. *The Sustainability Impact Assessment of Non-Urban Road Projects: A Fuzzy Approach.* In Proceedings of the 19th ARRB Transport Research Conference, Sydney, Australia, 6-11 December 1998.

Carter, S.J.B. and E.J. Gillian [1998]. *A Fuzzy Rule Based Roadside Vegetation Quality Index.* In Proceedings of the 19th ARRB Transport Research Conference, Sydney, Australia, 6-11 December 1998.

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Consulting Reports

Carter, S.J.B. [1999]. *An Expert System Model of National Highway Performance.* Environmental Dynamics project ED5055 the Tasmanian Dept. of Transport (in progress).

Carter, S.J.B. [1999]. *Environmental Indicators for the Tasmanian Transport Industry.* Environmental Dynamics Report ED5048 to the Tasmanian Dept. of Transport, Jan 1999.

Carter, S.J.B. [1997]. *DOT Transport Infrastructure Division: Environmental Review.* Environmental Dynamics Report ED5044 to the Tasmanian Dept. of Transport, Aug 1997.

Carter, S.J.B. [1996]. *Review of Proposed Environmental Indicators.* Environmental Dynamics project ED5040 for the Tasmanian Sustainable Development Advisory Council. September 1996. (Deliverables did not include a formal report.)

Carter, S.J.B. [1996]. *Towards an Interim State Policy on Land Use and Roads.* Environmental Dynamics Report ED5038 to the Tasmanian Dept. of Transport, June 1996.

Carter, S.J.B. [1996]. *Proposed UMT Spreyton Plant Air Quality Study.* Environmental Dynamics project ED5031, report to SEMF Consultants, Hobart, February 1996.

Carter, S.J.B. [1996]. *UMT Spreyton Plant: Proof of Evidence - Air Quality.* Submission to Land Use Planning Board, Environmental Dynamics project ED5033, May 1996.

Carter, S.J.B., M. Nunez, P. Manins, and D.G. Ross [1995]. Tamar Valley Airshed Study. Report to the Tasmanian Department of Environment and Land Management, June 1995.

Carter, S.J.B. [1995]. *Environmental Review of Proposed Road Upgrade of The Neck, Bruny Island.* Environmental Dynamics Report ED5023 to the Tasmanian Department of Transport, September 1995.

Hunter, J.R. and S.J.B. Carter [1994]. *The Physical Oceanographic Effects of Dumping Jarosite at Sea.* CSIRO Division of Oceanography Reports OMR-63/42 to OMR-68/42 inclusive, and OMR-70/42, September 1994. (Seven reports.)

Carter, S.J.B. and W.J. Thoburn [1990]. *CO_2 Emissions: Perspectives and Future Options for Canadian Electrical Utilities and for the Coal Industry.* Canadian Electrical Association Report 905 G 696, May 1990. (Published in English and French).

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1.0 INTRODUCTION

1.1 Background

In 1987, the Bruntland Commission brought the concept of sustainable development to the world stage, and the 1992 Earth Summit in Rio de Janeiro reinforced the call for nations to move towards an era of sustainability. The sustainability imperative has gained momentum in the 1990s, and has been accepted by many nations as a key goal of resource management and planning.

This research has been motivated by my belief that we should have a better understanding of sustainability at a practical level, and better tools with which to quantitatively assess the sustainability impact of projects, than is the case at present. My appreciation of the need for this research derives from over 15 years of environmental engineering experience, working on a wide range of projects in North America and Australia. My experience includes being an expert witness in three court cases relating to planning decisions.

1.2 Research Goals and Approach

The principal research goal was to develop a practical method to quantitatively assess the sustainability impacts of proposed projects. Several problems have hindered the development of such a method:

- sustainability is a concept which has been difficult to define and quantify;
- sustainability issues are often quantified by uncertain data; and
- the interactions between sustainability issues are complex, and often involve feedbacks between the issues.

Attempts have been made to extend traditional project assessment methods, such as benefit-cost analysis, to include environmental and social externalities. But it is hard to point to a single method that is used in practice, although approaches such as utility theory have been well understood for years. However, expert systems appear to be tailor-made for addressing such problems, and expert system software packages are now available which can be used on desk-top computers.

The following research objectives were set to help achieve the goal of developing a sustainability assessment method:

- define a practical way to consider and measure sustainability issues;
- explore ways in which sustainability information might be aggregated;
- develop an expert system to underpin the sustainability assessment method; and
- validate the sustainability assessment method, and explore how it might best be used, by applying it to several practical problems.

Tasmania is an ideal place to validate a sustainability assessment method. The State has an area of about 68,000 km^2, some 20 percent of which is world heritage wilderness. It has a population of about half a million people, and significant primary industry. Planning issues are of great interest to Tasmanians, and the Resource Management and Planning Appeal Tribunal considered about 1,000 cases over the period 1994-97.

The structure of this thesis is set out in Table 1.1.

Chapter 1.	Introduction.
Chapter 2.	Reviews our understanding of sustainability and its indicators.
Chapter 3.	Explores classical and fuzzy ways to aggregate sustainability indicators.
Chapter 4.	Explores aggregation using pattern recognition methods such as neural networks.
Chapter 5.	Describes a sustainability assessment method, using a fuzzy-rule system.
Chapter 6.	Illustrates and validates the method through two primary industry case studies.
Chapter 7.	Examines sustainability issues associated with non-urban road projects, and assesses the sustainability impact of Tasmania's new Western Explorer road.
Chapter 8.	Examines the use of multi-criteria decision-making techniques and genetic algorithms to select and optimise a preferred project option.
Chapter 9.	Summarises the conclusions of the research, and looks ahead to the future.

Table 1.1 Structure of the thesis.

2.0 THE SUSTAINABILITY IMPERATIVE

2.1 Brief History

Figure 2.1 outlines international, national, and Tasmanian milestone events in the history of environment protection legislation, and of the sustainability imperative.

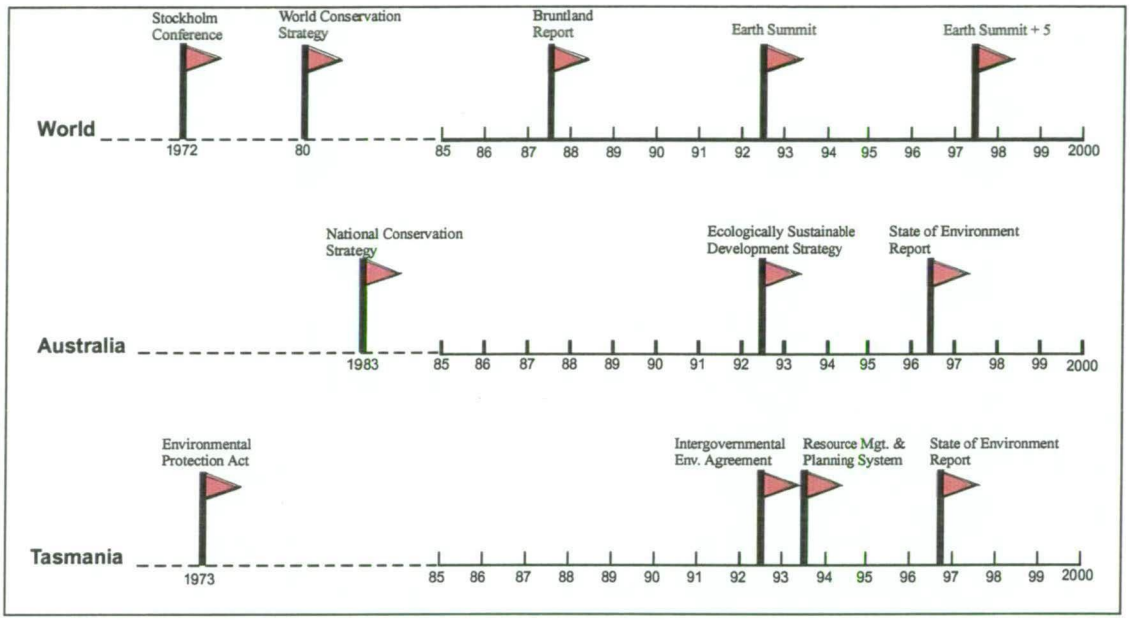


Figure 2.1 Milestone environmental and sustainability initiatives.

The environmental movement achieved international prominence in the early 1970s, and many national and regional governments enacted environment protection legislation in the period 1971-75. The United Nations Conference on the Human Environment, held in Stockholm in 1972, brought countries together for the first time to discuss environmental management issues in a global context, and provided an important forum for attempts to link ecological conservation to economic development. Environmental management philosophies continued to evolve, and the concept of sustainable development emerged in the 1980s. Moffat (1996) provides a good review of this subject. The World Conservation Strategy (IUCN, 1980), an early step towards understanding sustainability issues, aimed to integrate development and conservation issues, but largely neglected socio-economic concerns (Allen, 1980).

The two most significant events in the history of the sustainability imperative have been the Bruntland Commission's report, *Our Common Future*, (WCED, 1987); and the United Nations Conference on Environment and Development (UNCED, 1992), held in Rio de

Janeiro in June 1992, and widely known as the Earth Summit. The Bruntland Commission refined the concept of sustainable development, and brought it to the global stage, while the Earth Summit produced several important initiatives, including Agenda 21, a global action program for sustainability which was the consensus agreement of the 178 countries attending the conference; and the Convention on Biodiversity Conservation, ratified by Australia on 18 June 1993.

In Australia, a National Strategy for Ecologically Sustainable Development (ESDSC, 1992) was endorsed in 1992 by the Council of Australian Governments. The strategy, which is currently being reviewed, is supported by nine sectoral working group reports, and by three reports on intersectoral issues. In May 1992, representatives of all three levels of Australian government signed an Inter-Governmental Agreement on the Environment, which provides a framework to promote ecologically sustainable development, and to better integrate economic and environmental considerations in decision making (IGAE, 1992). Australia's progress in addressing its commitments regarding the Earth Summit is documented in its annual reports to the UN Commission on Sustainable Development.

The sustainability imperative is now accepted by all levels of Australian government, and is enshrined in environmental and planning legislation across Australia. Many professional organisations also endorse the goal of sustainability. The Institution of Engineers' Code of Ethics includes the tenet that its members should practice a sustainability ethic, and this tenet is supported by the Institution's *Policy on Sustainability,* which incorporates the principles of Agenda 21; and by its publications *Towards Sustainable Engineering Practice* and *Environmental Principles for Engineers*[1].

2.2 The Meaning of Sustainability

2.2.1 Definitions and Principles

The terms sustainable development, ecologically sustainable development, and sustainability, are used somewhat interchangeably in the literature. Table 2.1 gives some typical definitions of these terms, although there are many variations on these definitions, and many sets of supporting objectives and principles have been proposed. For example, the

[1] The author was a member of the Institution's National Committee on Environmental Engineering from 1994 to 1996, at which time the Institution's national environmental engineering society was formed. He is a past chairman (and present secretary) of the Tasmania chapter of the society.

Rio Declaration of the Earth Summit sets out 27 sustainable development principles (UNCED, 1992), building on those defined in the 1972 Stockholm Conference Declaration.

Ecologically Sustainable Development Using, conserving and enhancing community resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased (Australian National Strategy for ESD: ESDSC, 1992).
Sustainable Development Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations (Bruntland Commission: WCED,1987).
Managing the use, development and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic and cultural well-being and for their health and safety while sustaining the potential of natural and physical resources to meet the reasonably foreseeable needs of future generations; safeguarding the life-supporting capacity of air, water, soil and ecosystems; and avoiding, remedying or mitigating any adverse affects of activities on the environment (Tasmanian Resource Management and Planning System: DELM, 1996).
Sustainability The ability to maintain a high quality of life for all people, now and in the future, while ensuring maintenance of the ecological processes on which life depends, and continued availability of the natural resources needed (Institution of Engineers, Australia: IEAust, 1994).

Table 2.1 Typical definitions of sustainability and similar terms.

In New Zealand, the N.Z. *Resource Management Act (1991)* defines the term *sustainable management* as "managing the use, development and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic and cultural wellbeing and for their health and safety". This could also serve as a definition of sustainable development, and the term sustainable management has not found widespread usage outside New Zealand.

A review of the literature suggests that it is reasonable to define sustainability in terms of three component themes:

1. **Biodiversity:** Biological diversity and integrity.
2. **Socio-economic:** Well being and equity within and between generations.
3. **Physical environmental:** Local, regional and global environmental well being.

These sustainability themes match the way in which many planners and engineers think about projects. Human quality of life depends on all three themes. It is more than social well being, since our appreciation of the physical environment and biodiversity extends beyond their use as resources, and biodiversity is widely recognised to have intrinsic value,

independent of humans. Also, socio-economic factors, which relate to purely technical, military or political aspects of a project are not fundamental to a definition of sustainability, but only provide constraints on viable decisions. Similarly, the financial aspects of a project are only important in so far as they relate to community well being. Chapter 8 examines how to select and optimise a preferred project option, given these constraints.

The sustainability themes defined above avoid reliance on the concept of an ecosystem. An ecosystem is an aggregate of plants, animals and other organisms, together with the physical environment on which they depend. It is thus a holistic concept, which is best quantified in terms of its (strongly coupled) component themes of biodiversity and physical environment.

Mitchell et al. (1995) note that inter-generational equity requires maintenance of some level of environmental resources and ecological systems; and that intra-generational equity requires people to have greater equality in access to the environment, and also to share the costs of human activity (the user-pays principle). Some workers have studied sustainability from an economic viewpoint, and have suggested the concepts of "weak" and "strong" sustainability (Daly and Cobb, 1989; Common and Perrings, 1991; Moffatt, 1996). Weak sustainability requires that the overall stock of natural capital and human-made capital remains constant over time, such that some assets can be reduced provided others are increased to compensate. Strong sustainability takes the position that it is not sufficient to protect the overall level of capital, and requires that stocks of non-replaceable natural capital should also be maintained. These terms have not met with wide acceptance, and are not adopted by this thesis.

2.2.2 Conceptual Models

A number of conceptual models have been proposed to provide a framework for organising information about the interactions between humans and the environment.

<u>Pressure-State-Response model (OECD, 1994; Figure 2.2)</u>

Most nations, including Australia, use the PSR model for State of the Environment reporting. The model assumes that human activities exert pressures on the environment, thus changing its state; and that society responds to these changes. Indicators are divided into *state indicators*, which measure what is happening to the environment; *pressure indicators*, which measure environmental pressures caused by humans; and *response indicators*, which measure what society is doing to respond to environmental changes.

Population-Environment-Process model (Statistics Canada, 1994; Figure 2.3)

Some statistical agencies prefer the PEP model when linking socio-economic activity to environmental impacts. Australia's first State of the Environment report (SEAC, 1996) follows a PSR format, while the accompanying statistics document, *Australians and the Environment* (ABS, 1996), follows a PEP format.

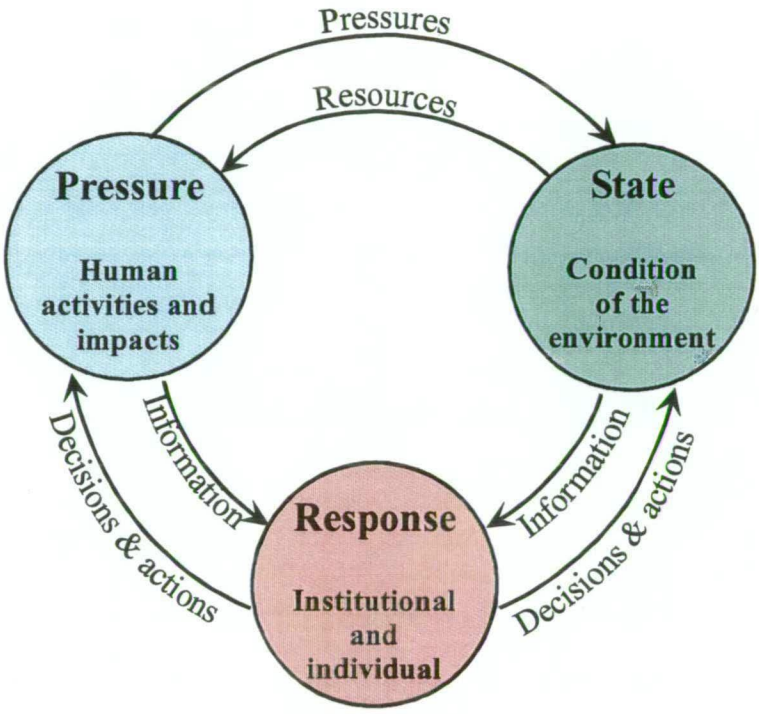


Figure 2.2 Pressure-State-Response model.

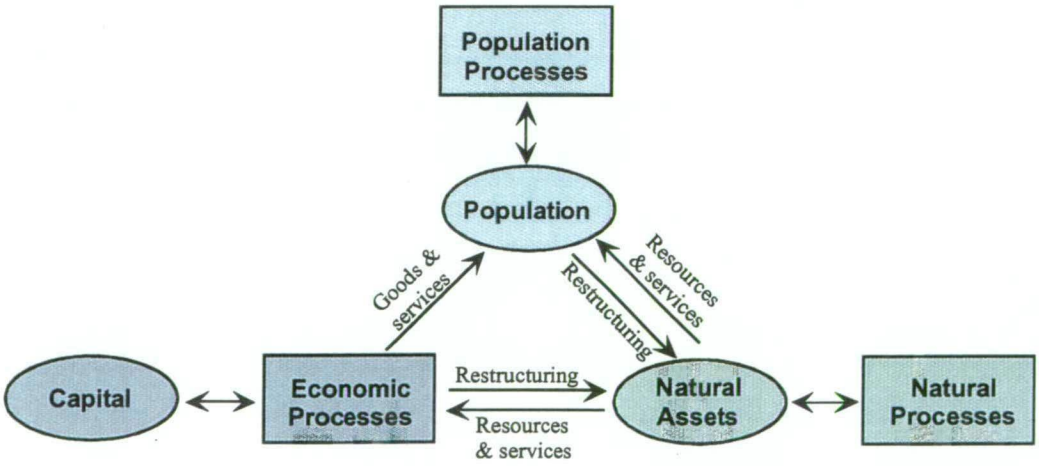
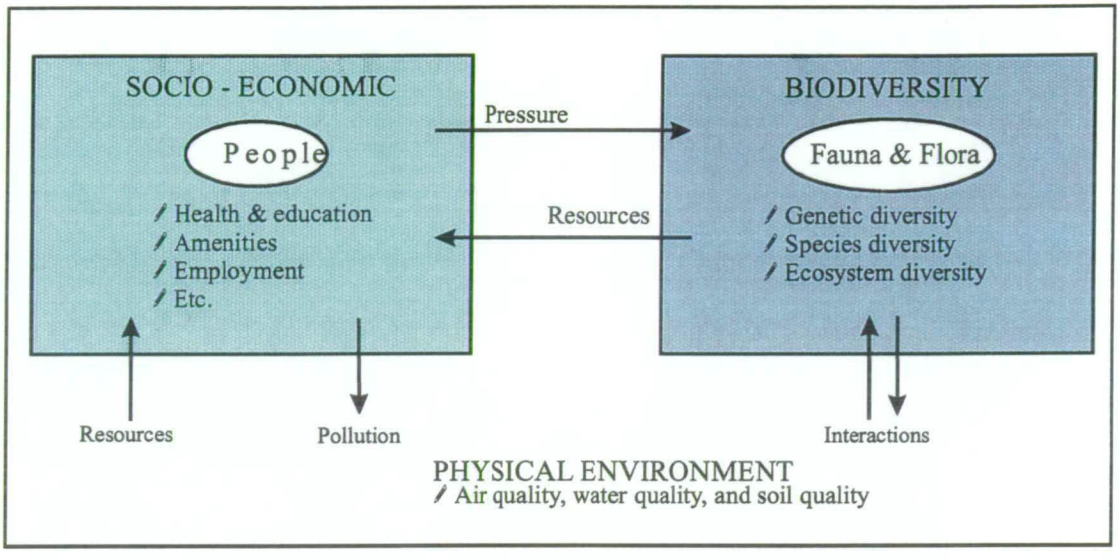


Figure 2.3 Population-Environment-Process model.

Sustainability interaction model (Figure 2.4)

This model illustrates the principle interactions between the three sustainability themes defined above, and has been adapted by the author from a human interaction model proposed by Hammond et al. (1995). An important feature of the model is the secondary role played by economic processes.

Figure 2.4 Sustainability interaction model.



2.2.3 Discussion

Critics have characterised sustainable development as an oxymoron, and as too nebulous a concept to be of value (*e.g.* Tucker, 1994). Clearly there is some internal contradition in the term, but debate about the meaning of sustainability has largely moved on to examining ways in which it can be measured (Moffatt et al., 1994). Development in the sense of continuous expansion clearly cannot be sustained, but it is widely accepted that sustainability does not refer to an unchanging situation. In rebutting this notion, Sustainable Seattle (1995) quotes Mr Kenneth Boulding as follows:

> "The concept of sustainability does not refer to some equilibrium state… but to a sustainable evolutionary process of continuous change. We don't want the existing world structure to be sustainable. We want to improve it".

Regarding the use of non-renewable resources, such as fossil fuel, Goodland et al. (1992) assert that the rate of resource usage is important, since this gives society and nature time to adjust to a changing situation. This idea has been taken up in the definition of sustainable development offered by Tasmania's Resource Management and Planning System (Table 2).

In any event, it is not futile to assess the sustainability impact of a proposed project which uses non-renewable resources, since many aspects of such a proposal will likely benefit from a strategic analysis.

Society has progressed far in addressing environmental management issues, and the progress has required a paradigm shift in our approach to project planning. Some 25 years have passed between enactment of environment protection legislation in the early 1970s, and the release of the ISO 14000 environment management standards in 1995. Environmental standards and best practice environmental management for many industries are still being refined. The more recent concept of sustainable development is also taking time to translate into practice. The goal is easy to grasp, and global awareness of environmental problems has driven efforts to adopt sustainable practices, but it takes time to implement the demand that planning be more visionary and better integrated than before.

A fundamental challenge ahead for sustainable planning is to consider the optimum human population which a region can support. The 1994 Population Summit, held in Cairo, failed to reach consensus on population control. Australia does not have a formal population policy, the government's position being that there are diverse community views about the objectives and nature such a policy might have, and that it would thus be inappropriate to specify an optimal population level (ESDSC, 1992). However, calculations of ecological footprints suggest that Australia's population may already be too large to be sustainable (see Chapter 3). DEP (1997) reports that environmental degradation is a sign that Western Australia has exceeded its carrying capacity in some areas, but notes that the State has such a strong growth ethos that it is difficult for some people to even contemplate the idea of limiting population growth. Planning philosophies based on this kind of colonial expansionist thinking are inherently unsustainable.

2.3 Sustainability Indicators

2.3.1 Background

Indicators set out conditions and trends associated with various issues, and one way to assess the sustainability impact of a proposed project is to predict how it will change an appropriate set of sustainability indicators. This is consistent with Agenda 21, which says that *indicators of sustainable development need to be developed to provide solid bases for*

decision making at all levels, and to contribute to self regulating sustainability of integrated environmental and development systems (UNCED, 1992: Ch 40).

Much work has been devoted to developing sustainability indicators (Hammond et al., 1995; Kuik and Verbruggen, 1991; Moffat, 1996; Mitchell et al., 1995). Sustainability indicators are herein defined in terms of biodiversity, socio-economic, and physical environmental themes, but other approaches are possible, provided that indicator selection is underpinned by a coherent methodology, with agreement on the sustainability definition and vision which the indicators are intended to support (Mitchell et al., 1995).

Examples of alternative ways to organise indicators are:

- According to issues. The Australian State of the Environment report uses seven reporting themes (e.g. inland waters, biodiversity: SEAC, 1996). Agenda 21 is also organised according to issues (UNCED, 1992), while Adriannse (1993) and Hammond et al. (1995) have proposed issue-based indicators to assist in assessing policy performance.

- Environmental aspects. This term is associated with environmental management systems, and refers to the aspects of an organisation's business and operations which interface with the environment. Details are given in the international standard ISO 14001, adopted as an Australian Standard by Standards Australia in 1996.

- Human-environment interactions. The World Bank has suggested organising indicators according to four broad types of human interaction with the environment, namely pollution, resource depletion, ecosystem risk, and environmental impact on human welfare (World Bank, 1995).

2.3.2 Sustainability Visions

The application of an ethos of sustainability in a given region results in a sustainability vision for that region. A suitable set of sustainability indicators can quantify the sustainability vision, and a value can be agreed for each indicator which denotes achievement of the vision with respect to that indicator.

One expects a nested hierarchy of sustainability visions, rather than a single vision against which all decisions are measured, and the sustainability vision for a large region will

actually require local variations. Also, the sustainability vision for a large area must be broader than for a small area, since a large area will comprise a mosaic of land types and usages for which overly detailed visions are inappropriate. For example, some aspects of human quality of life need the support of heavy industrial areas, and development of these areas will be guided by visions which are essentially 'frontier economic' philosophies. Conversely, some aspects of biodiversity conservation require large areas of habitat undisturbed by human activities, and such areas must conform to a 'deep ecology' vision. However, planning for many areas will be guided by visions in which compromise is possible between the sustainability themes.

Planning decisions should move an area towards the sustainability vision for the local area, assuming that this vision respects the visions for the larger areas in which it is nested. If a sustainability assessment of different project options results in different patterns of indicator changes, such that the planning decision is not obvious, then the assistance of a multi-criteria decision method may be needed (see Chapter 8).

There has been considerable effort by local governments to develop sustainability visions and supporting indicators, as part of the Local Agenda 21 initiative promoted by Chapter 28 of Agenda 21 (UNCED, 1992). The 1997 Pathways to Sustainability Conference, held in Newcastle, New South Wales, estimated that 2,000 local governments around the globe had developed Agenda 21 strategies in the five years since the Earth Summit (Pathways, 1997). Of course, Australia alone has about 700 local governments - the exact number is always changing - but the trend is encouraging. Brown (1997) discusses sustainability and local government initiatives in an Australian context.

Examples of some of the better known Local Agenda 21 programs are summarised below. In most cases, programs were established following extensive community consultation. In some cases, the sustainability indicators selected by local governments are of a general nature, but many are region specific.

Seattle, Washington, USA.

The Sustainable Seattle project is frequently referred to in the literature. The project started in 1993, and the group of about 40 indicators which has evolved spans five areas: physical & natural environment; population & resources; economy; youth & education; and health & community (Sustainable Seattle, 1995). General indicators include population, distribution

of personal income, and juvenile crime, while indicators specific to Seattle's situation include wild salmon numbers, and ethnic diversity of teachers.

Santa Monica, California, USA.

Santa Monica's Sustainable City Program was formally adopted by the City Council in late 1994. The program tracks about 20 indicators spanning four areas: resource conservation; transportation; pollution prevention & public health protection; and community & economic development (Santa Monica, 1996; Kubani, 1997). General indicators include energy usage, and reduction in use of hazardous materials, while indicators specific to Santa Monica include dry weather discharges from storm water drains, and annual ridership on municipal buses.

Hamilton-Wentworth, Ontario, Canada.

Hamilton-Wentworth's Vision 2020 Sustainable Community Initiative was developed with assistance from the International Council for Local Environmental Initiatives, which is well known for its work in promoting local Agenda 21. The program tracks about 30 indicators, with an annual environment day to publicise indicator trends (Thoms and Pearce, 1997).

2.3.3 Candidate Indicators

At an international level, the U.N. Environment Program has produced GEO-1, a Global State of the Environment Report 1997 (UNEP, 1997). A second report, GEO-2, to be issued in 1999, will use a limited set of global environmental indicators. The OECD also publishes a biannual compendium of global environmental data.

Many nations and regional governments regularly publish State of the Environment reports. These reports are a fruitful source of indicators, often broadly interpreting 'environment' as including the physical environment, biodiversity, human settlements and cultural heritage. As noted, Australia's first State of the Environment report, SEAC (1996) has seven reporting themes, and sets of key indicators have been developed to support each reporting theme, in preparation for the next national State of the Environment report.

At a regional level, the New South Wales 1995 and 1997 State of the Environment reports provide the most detailed indicator sets to date. The review of indicators by Harding and Eckstein (1996), for the NSW environment authorities, is also comprehensive. Tasmania's first State of the Environment report provides a good discussion of environmental issues in the State, but for the most part only identifies indicator themes (SDAC, 1996).

Biodiversity indicators

Biodiversity indicators are poorly established, but it is generally agreed that three levels of biodiversity should be monitored: ecosystem diversity, species diversity, and genetic diversity (Reid et al, 1993). The Interim Biogeographical Regionalisation of Australia classification provides a framework for applying biodiversity indicators at the regional and national levels, and Figure 2.5 shows Tasmania's eight IBRA regions. A biogeographical region is distinguished from adjacent regions by its broad physical and biological characteristics (SEAC, 1996).

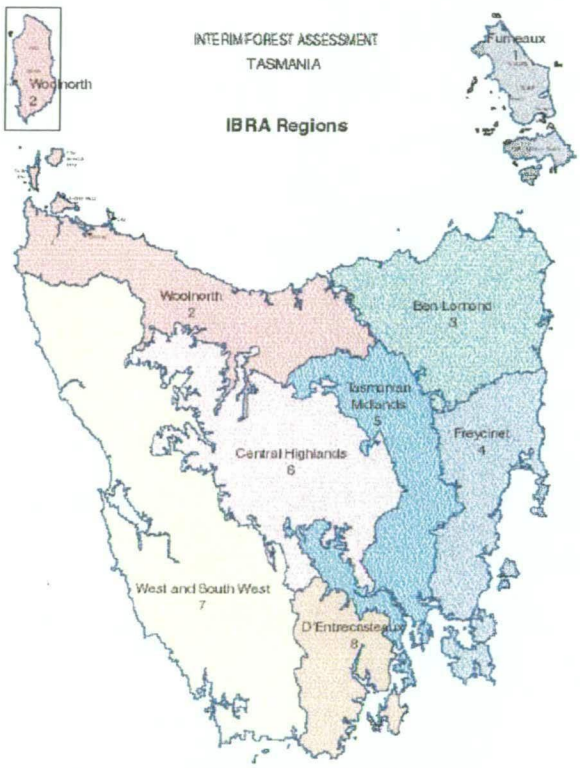


Figure 2.5 Tasmania's eight IBRA regions (courtesy Forestry Tasmania)

The 1996 Australian State of the Environment report used threatening processes such as land clearance, as biodiversity indicators (SEAC, 1996), but the next report will likely be based on Saunders et al. (1998), who recommend 12 pressure, 17 condition, and 34 response indicators (building on the work of Brown et al., 1997).

Socio-economic indicators

These indicators are well established, and include health, education & training, employment, income & wealth, housing, crime, and amenities. Where appropriate, indicators should distinguish between males and females (e.g. life expectancy at birth); and should measure the distribution of the value in the community. (ABS, 1997a; SEAC, 1996, p3-33).

Physical environment indicators

These indicators are also quite well established, and are usually supported by standards for air quality, soil quality and so on. For example, greenhouse warming is a global air quality issue, and associated indicators are fossil fuel usage and greenhouse gas emissions, with emission reduction targets set by the Kyoto Protocol of December 1997. Urban air quality is a more regional concern, and associated indicators are usually ground level concentrations of particulates (as PM_{10}), Pb, SO_x, NO_x, O_3, and CO, measured over agreed averaging

periods. Australia's new (1998) National Environment Protection Measure for air ambient quality sets out standards for these pollutants.

2.3.4 Indicator Selection

Many sets of criteria have been developed to screen candidate indicators for various applications. DEST (1994) listed 17 criteria, which Alexandra et al. (1998) have combined into five groups known as the SMART filter (Simple, Measurable, Accessible, Relevant and Timely). The author proposes a similar of core criteria to screen sustainability indicators, listed in Table 2.2, in which "Scale" replaces "Timely", "Credible" replaces "Simple", and "Accessible" is replaced by the "Critical Values" criterion.

Relevance	The indicator represents a fundamental aspect of sustainability of relevance to the situation being assessed.
Measurable	A data set exists to support the indicator, and new values of the indicator can be measured using standard methodologies. The data are clearly defined, verifiable, scientifically acceptable, and reproducible.
Critical values	Intervention and sustainability threshold values can be defined for the indicator.
Credibility	The indicator and the value it represents are sufficiently understandable and credible that they are accepted by the community and decision-makers.
Scale	The indicator can be reliably and consistently evaluated on the desired geographic and time scales, and can provide early warning of change.

Table 2.2 Suitability criteria for indicators used in sustainability assessments.

The critical values criterion means that it must be possible to define an indicator value beyond which some form of intervention is suggested, and also to define a threshold value beyond which the indicator is consistent with the sustainability vision. A number of other attributes are desirable, but it is rare for an indicator to satisfy all desired criteria, and the sustainability aspects of a project must usually be described by a set of less than ideal indicators.

It may also be appropriate to assign weights to indicators, but the three sustainability themes are considered to be of equal importance, and weighting should only reflect the importance of indicators to the assessment of an individual theme, a point discussed further in Chapter 5. Sustainability indicators should also be selected to reflect the geographic scale and time period being considered. Figure 2.6 shows how indicators describing the sustainability vision for a local region are nested within the indicators for larger scale visions.

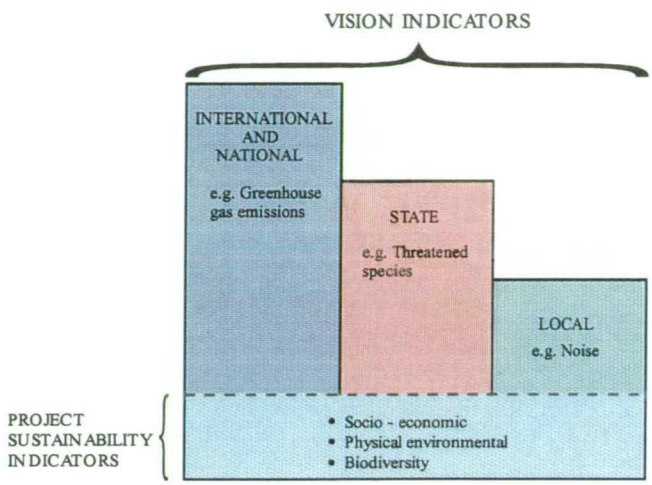


Figure 2.6 Organisation of sustainability indicators.

Table 2.3 gives examples of indicators appropriate for different situations: jarosite dumping is discussed by Hunter and Carter (1994), and climate change by Carter and Thoburn (1990). It is important that indicators be specified with reference to their areas of influence, and time frames, and this requirement also applies equally to indicator baseline values, intervention values and sustainability threshold values. For example, Table 2.3 suggests using ambient SO_2 concentration as a regional indicator for acid rain, but this indicator might also be used in a local context, and for either long or short term periods. However, the associated intervention and sustainability threshold values would differ, since air quality standards depend on the averaging time, and on the background concentrations of airborne pollutants in an airshed.

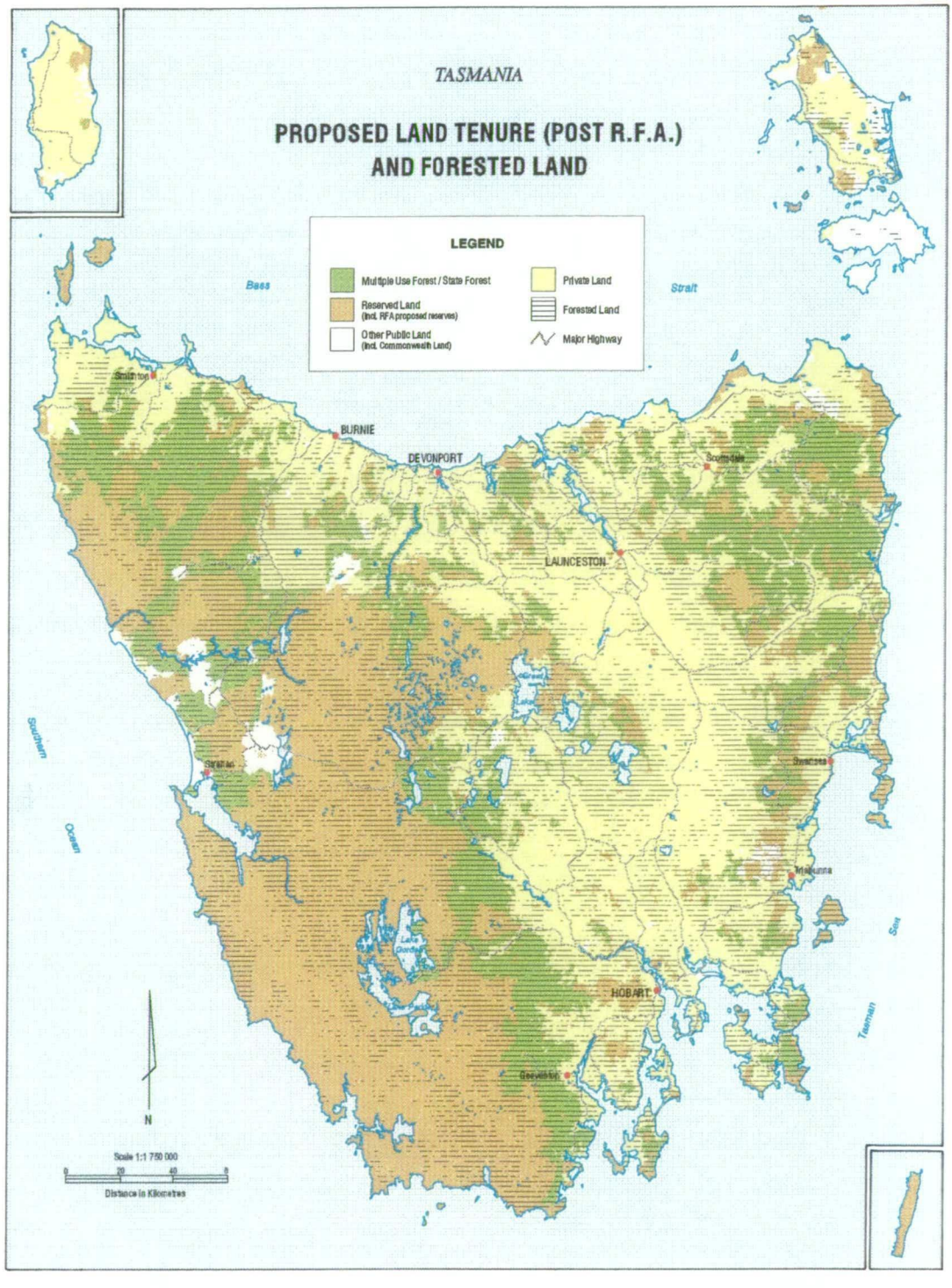
	Climate change	**Acid rain**	**Ocean dumping of jarosite**
Long term	Sea level, global mean temperature.	Extent or number of affected lakes & forests	Population and well being of marine species in southern Tasmanian waters.
Short term	CO_2 emissions.	SO_2 emissions from major sources	Ambient concentrations of heavy metal in seawater
Local	Coastal vulnerability index.	Area denuded of vegetation near source.	Amount of jarosite on sea bed
Regional	Mean annual rainfall and temperature.	Soil acidity and ambient SO_2 levels	Southern Bluefin Tuna populations

Table 2.3 Examples of indicators appropriate for different time and distance scales.

2.4 Sustainable Planning for Tasmania

Tasmania has a land area of about 68,050 km^2, including its satellite islands, and Figure 2.7 shows the distribution of land tenure following the 1997 Regional Forests Agreement. The lands administered under the *National Parks & Wildlife Act (1970)* include world heritage wilderness areas, which comprise 13,700 km^2 of central and south-west Tasmania.

Tasmania's population in 1996 was just over 474,000 people. The cities of Hobart, Glenorchy, Clarence, and Launceston together account for over 40 % of the State's



Land tenure	Percentage
Private property	39.3
Lands administered by the forestry commission	23.3
Lands administered under National Parks & Wildlife Act	21.2
Non-allocated Crown land	10.2
Other lands	6.0
	100.0

Figure 2.7 Tasmanian land tenure and forests (courtesy of Forestry Tasmania).

population, and the north coast communities account for a further 20 %. The State's population growth rate has averaged less than 0.5 % in the 1990s, the lowest of any Australian State (ABS, 1997b). The Tasmanian Government believes that population growth will result in economic benefits, and accordingly established a Task Force in July 1996 to increase the State's population. While this may be true, no consideration has been given to any associated negative impacts of an increased population, nor to the type of economic growth which might best suit Tasmania (Mercury, 1997; Mr M. Fisher, Task Force executive officer, pers. comm., 8 Sept. 1997).

The complicated mosaic of land usages shown in Figure 2.7, and pro-development initiatives based on mainly economic considerations, highlight a need for a sustainability vision for the State, with local visions as appropriate. Such strategic planning is beginning to drive development of some components of the State's economy, for example the forest industry (see Chapter 6), but no umbrella sustainability vision for Tasmania has yet been agreed, and questions such as what is the optimum population for Tasmania have not been considered.

In 1993, Tasmania introduced a Resource Management and Planning System, similar to New Zealand's *Resource Management Act (1991)*, with the objectives shown in Table 2.4.

Objectives of the Resource Management and Planning System.
1. Promote the sustainable development of natural and physical resources and the maintenance of ecological processes and genetic diversity.
2. Provide for the fair, orderly and sustainable use and development of air, land and water.
3. Encourage public involvement in resource management and planning.
4. Facilitate economic development in accordance with objectives 1, 2 and 3.
5. Promote the sharing of responsibility for resource management and planning between the different spheres of Government, the community and industry in the State.

Table 2.4 Objectives of Tasmania's resource planning legislation.

The Resource Management and Planning System (RMPS) is an integrated package of legislation with sustainable development as its principal goal. Figure 2.8 sets out the main features of the RMPS, and DELM (1996) provides further details. The system provides an development application assessment process which is considered to be an example of international best practice resource management and planning legislation (Edwards, 1997).

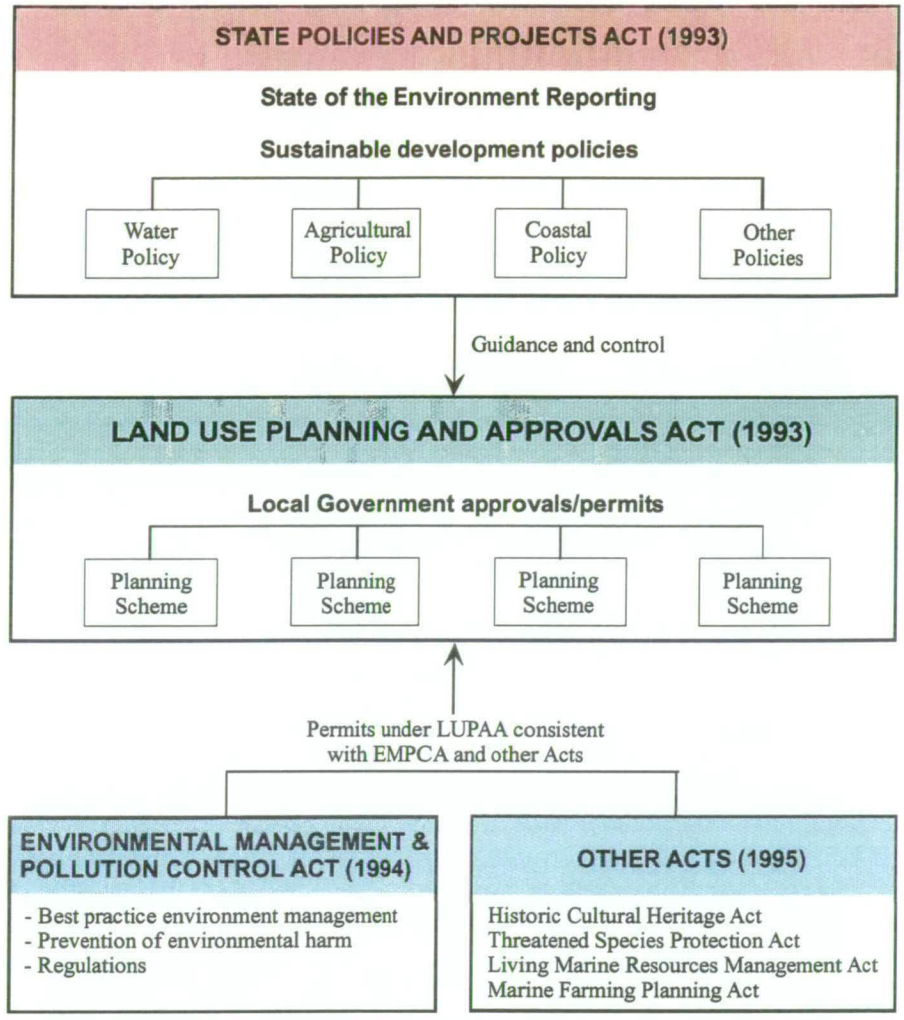


Figure 2.8 Tasmania's Resource Management and Planning System.

The *Land Use Planning and Approvals Act (1993)* and the *Environmental Management and Pollution Control Act (1994)* form the core of the system. LUPAA (1993) requires local government planning schemes to accord with the objectives of the RMPS, and sustainable development policies interpret these objectives in various areas.

Development permits are issued by Councils under LUPAA (1993), and developments must comply with EMPCA (1994), and its supporting suite of legislation. EMPCA (1994) aims to prevent environmental harm, and promotes best practice environmental management. It has powerful enforcement provisions, and can lift the corporate veil in prosecuting offences. The RMPS also provides for planning decision appeals and prosecution of environmental offences to be initiated by third parties, including the community at large.

The RMPS is substantially different from earlier approaches to planning, and implementing the system is proving to be a challenge, although overall it is working quite well. Reviews

by TBA Planners (1996) and Edwards (1997) noted that sustainable development policies have been difficult to develop. By early 1998, only the Coastal Policy and the Water Policy had been approved by parliament, while the Road Policy had been withdrawn after extensive criticism (Carter, 1996). However, the suite of National Environment Protection Measures being developed by the National Environment Protection Council will also have the force of sustainable development policies in Tasmania.

Another problem is that Tasmania still has some 100 planning schemes, in spite of a rationalisation of local government areas in the early 1990s, from 46 to 29. Further local government amalgamations have been proposed, and a model planning scheme is being developed to assist local governments to revise their schemes, and achieve consistency of planning across municipal boundaries.

Hogue (1996) has proposed a vision statement based on the RMPS objectives described above, together with eleven goals and sub-goals which might be monitored using indicators. Similar vision statements have been developed elsewhere, for example NZMOE (1995). However, while overarching statements are necessary for clarity, it is crucial that any vision be supported by indicators that can measure the degree to which the vision is being achieved.

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3.0 INDICATOR AGGREGATION 1: CLASSICAL VS FUZZY RULE METHODS

3.1 Introduction

Chapter 2 proposed that sustainability is best measured in terms of indicators grouped into three themes (biodiversity, socio-economic, and physical environmental). Chapters 3 and 4 examine ways in which a set of indicators can be combined into a more concise description of the sustainability issues associated with a project. This chapter considers situations in which the relationships between an index and its component indicators are reasonably well understood, and compares traditional aggregation methods with fuzzy rule systems.

Aggregation is an important aspect of data processing. Figure 3.1 shows how raw field data, indicators, and indices together form an information pyramid, in which increasing aggregation simplifies the communication of information to decision-makers and the media (Hammond et al., 1995; SEAC, 1996). The dash line in Figure 3.1 shows that the difference between an indicator and an index is not distinct, and indeed one encounters ambiguous phrases in the literature, such as 'using an index as an indicator of some condition'.

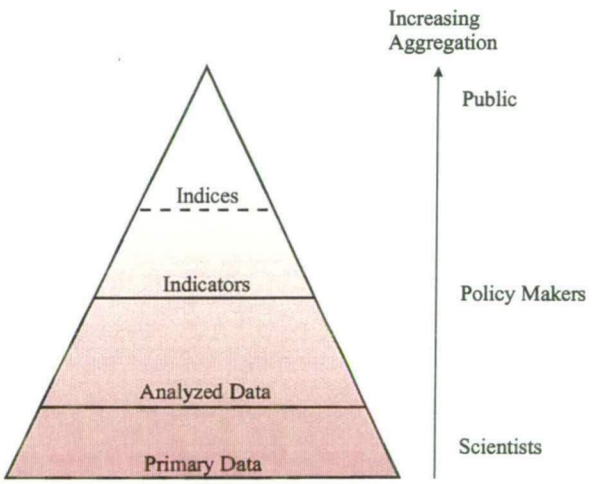


Figure 3.1 The information pyramid.

In general, an indicator is a quantity which is closely associated with the value it represents, while an index is a more abstract quantity that results from aggregating indicators. A sustainability value can be described either by many indicators, which together provide a detailed picture of the value, or by a small number of fingerprint indicators, or by an index that provides a bulk description of the value. Kuik and Verbruggen (1991) aptly describe aggregation as a compromise between scientific accuracy and the demand for easily understood information.

For example, consider an urban airshed. A scientific description of its air quality would need information about the local air pollution meteorology, and the associated temporal and spatial distribution of airborne contaminants. However, a regulatory authority would likely

accept concentrations of the usual criteria pollutants as air quality indicators (PM_{10} particulates, CO, SO_x, NO_x, Pb and O_3). For the purpose of providing air quality information to the public, it is common for two or more of these six standard indicators to be aggregated into an air quality index. In the case of a Tasmanian population centre, however, particulates from winter time domestic wood heater emissions are the only significant concern, and PM_{10} particulate concentrations could be used as a fingerprint air quality indicator, in lieu of calculating an air quality index.

The characteristics of a good index are the same as those of a good indicator (Chapter 2), with the caveats that success of an index also depends on the selection of appropriate constituent indicators, and on the use of an appropriate aggregation method. The aggregation process is also irreversible, in the sense that an average cannot be disaggregated into its original set of numbers. Nevertheless, aggregation is to be encouraged when the required description of the sustainability issues associated with a project allows such simplification.

The aggregation of the three sustainability themes into a single "quality of life" index would have the strong appeal of simplicity. Section 3.3 examines several approaches to developing such an index, but none has found much favour with environmental professionals, with the possible exception of the "ecological footprint" index (which is hard to apply at a project-specific level). Also, quality of life is not completely synonymous with sustainability (for example, as noted in Chapter 2, biodiversity is recognised by many to have intrinsic value), and in the author's opinion better project planning for sustainability will generally result from keeping the three principal themes distinct.

3.2 Classical Aggregation Functions

Classical aggregation functions are usually based on the generalised mean:

$$h_\alpha(a_1, a_2, \ldots, a_n) = \left[\frac{1}{n}(a_1^\alpha + a_2^\alpha + \ldots + a_n^\alpha)\right]^{\frac{1}{\alpha}}$$

As $\alpha \to \pm\infty$, the generalised mean reduces to the minimum and maximum operations respectively, which are commonly used as aggregation functions. For α = -1, 0 and +1, it produces the three basic mean functions (proofs are given in Klir and Yuan, 1995):

- Harmonic mean $h_{\alpha=-1}(a_1, a_2, ..., a_n) = \dfrac{n}{(a_1^{-1} + a_2^{-1} + ... + a_n^{-1})}$

- Geometric mean $h_{\alpha=0}(a_1, a_2, ..., a_n) = (a_1 \cdot a_2 \cdot ... \cdot a_n)^{-n}$

- Arithmetic mean $h_{\alpha=+1}(a_1, a_2, ..., a_n) = \dfrac{1}{n}(a_1 + a_2 + ... + a_n)$

Aggregating a set of indicators requires consideration of the weight to be given to each indicator. For example, the geometric mean can be extended as follows:

$$h_{\alpha=0}(a_1, a_2, ..., a_n; z_1, z_2, ..., z_n) = (a_1^{z_1} \cdot a_2^{z_2} \cdot ... \cdot a_n^{z_n})^{-n} \qquad \sum z_i = n$$

Consideration of weighting is unavoidable, since the default assumption is that each indicator holds equal weight. However, weighting should only be used to reflect the importance of indicators in contributing to an index within a given sustainability theme, since the three themes are of equal importance. Nijkamp et al. (1990) review methods of directly estimating weights for a linear arithmetic weighting function, including the trade-off method, the rating method, the ranking method, scaling, and paired comparisons. Jesinghaus (1994) describes an expert system approach (EXSTACY) to providing weighting coefficients for aggregating environmental pressure indicators.

Many classical index methods are simple. For example, traditional roadside vegetation quality indices are based on scoring methods (see the case study below), the Resource Assessment Commission used weighted summations of economic and environmental quantities to examine forest management options (see the case study in Chapter 6), while the Sydney regional air quality index uses a maximum operator applied to the hourly average observed concentrations of airborne pollutants.

An example of a more complex index method is the beach pollution index developed for application around Sydney in New South Wales (Achuthan et al., 1985). Beach pollution at the time was mainly due to sewage from coastal outfalls, and the indicators which a beach patrol could measure were counts of grease particles on the beach, materials of sewage origin on the beach and in the water, and turbidity of the sea beyond the breakers.

Achuthan et al. (1985) considered 15 index candidates, and plotted each candidate against faecal coliform densities obtained from surveys of 21 beaches in 1984. They proposed the following index, with a correlation coefficient of 0.55.

Beach pollution index = $I_1 + I_2 - 1$

Where $I_1 = \sqrt[1/10]{(G+1)^5(MB+1)^2(T+1)^2(MWT+1)}$ and $I_2 = \max(G, MB, T, MWT)$

and

G = code (0,1,2,3) for number of grease particles on beach
MB = code (0,1,2,3) for materials of sewage origin on beach
T = code (0,1,2,3) for turbidity beyond breakers
MWT = code (0,1,2,3) for materials of sewage origin in water

The index thus combined a weighted geometric average and a maximum operator, and ranged from 0 to 6, representing no pollution and high pollution respectively. Use of the index ceased in the early 1990s, following the engineering of deep water sewage outfalls, after which beach pollution became associated with stormwater runoff, and thus with rainfall. Unfortunately, the original survey data was lost during a series of computer upgrades, and it is not possible to determine whether an expert system index method might have improved upon the relatively low correlation coefficient.

3.3 Resource Accounting Methods

Resource accounting provides an alternative approach to quantifying regional sustainability. Most resource accounting indices do not fully describe sustainability issues, particularly in the area of biodiversity conservation, and they are hard to apply at a project-specific level. However, these indices can provide valuable insight into the sustainability of larger regions.

The ecological footprint is perhaps the most popular sustainability index based on resource accounting. It is discussed in Australia's first State of the Environment Report (SEAC, 1996), and Houghton (1998) has suggested using it to analyse Australia's transport infrastructure. The index was proposed by Rees (1992), who noted that the resources needed by a community could be represented by an area of land, which he termed its ecological footprint. The index is calculated from food, housing, transportation and other community needs, by associating these needs with equivalent land areas, and summing the areas (Wackernagel and Rees, 1996).

Other resource accounting indices are based on environmental economics, and often use either energy or money as an accounting unit. Money is not a fundamental aspect of sustainability (not every human society uses money), but any index must overcome the problem of how to add unlike quantities, and money is as valid a common unit for an index as any other. Moffatt et al. (1994) and Moffatt (1996) used several such indices to study the sustainability of Scotland's development, with the conflicting results shown in the Table 3.1.

Index	Measure	Assessment
Green GNP (net natural product).	Money	Sustainable
Weak sustainability index.	Money	Unsustainable
Net primary production	Energy / capita	Marginal
Ecological footprint	Area / capita	Unsustainable
Index of sustainable economic welfare (ISEW).	Money	Sustainable

Table 3.1 Sustainability index methods applied to Scotland by Moffatt et al. (1994).

The Index of Sustainable Economic Welfare (ISEW) is the best known of the indices examined by Moffatt et al. (1994) and Moffatt (1996). It was developed by Daly and Cobb (1989), and refined by Cobb and Cobb (1993), and it is calculated as follows:

ISEW = {personal consumption + non-defensive public expenditures + capital formation}
- {defensive expenditures + environmental damage costs + natural capital depreciation}

Moffatt and Wilson (1994) and Moffatt (1996) pursued the detailed application of the ISEW to Scotland, and concluded that there was a widening gap between the traditional measure of development, the Gross Domestic Product, and the ISEW. However, their calculations were weakened by poor data availability and accuracy, and by the assumptions which had to be made in order to calculate index components such as the environmental damage costs. Such problems are commonly encountered by resource accounting exercises.

An example of an energy-based resource accounting measure is the Enhancement of Carrying Capacity Options (ECCO) model developed in the early 1980s with the support of the United Nations. The model is described by the papers presented in Gilbert and Braat (1991). In brief, it is a dynamic feedback model which links variables such as industrial output, energy demand, population, and agricultural capital. It was applied in pilot studies of Kenya and Mauritius, and later applied to other countries. ECCO is premised upon an early definition of sustainability as the energy produced by a nation compared to the energy used to drive its economy. However, the model's ability to examine the effect of population

growth on resource and development issues, and its consideration of feedbacks between variables, make it a useful tool for examining large scale aspects of sustainability.

3.4 Fuzzy Aggregation Methods

3.4.1 Fuzzy Logic

Fuzzy logic was introduced by Lotfi Zadeh (Zadeh, 1965), and fuzzy methods are now accepted as valuable tools with many applications in engineering and other fields. However, most applications to date have been in the field of control systems. A literature review shows that there have been relatively few applications of fuzzy theory to environmental problems, and that most such applications deal with decision-making rather than system analysis (*e.g.* Bosserman and Ragade, 1982). Nevertheless, many environmental problems are tailor-made for analysis by fuzzy methods, and it is likely only a matter of time before these tools achieve common usage by environmental professionals.

Fuzzy methods are based on simple mathematics and on natural language. They are ideal for handling uncertain data, and can model non-linear systems in an easily understood fashion. Fuzzy mathematics is an extension of classical mathematics, and give the same results if crisp (*i.e.* non-fuzzy) data are being processed. Introductory texts include Klir et al. (1997), Klir and Yuan (1995), Yen et al. (1995), Tereno et al. (1992), and Zimmerman (1991).

The development of a fuzzy rule system is illustrated in the case studies presented below. In brief, input values are fuzzified using membership functions, and then evaluated using a set of rules provided by an expert, which typically have the form:

If (*height* is *tall*) OR (hair is *little*) THEN (*age* is *old*)
If (*height* is *small*) AND (*hair* is *lots*) THEN (*age* is *young*)

Where *height,* and *hair* are the input variables and *age* is the output variable. The variable *height* is fuzzified using the membership functions *tall* and *small*, the variable *hair* is fuzzified using the membership functions *little* and *lots*, and the variable *age* is fuzzified using the membership functions *old* and *young*.

A membership function, μ_A, of a fuzzy set, A, maps elements, x, of the Universal set, X, to the real number interval [0,1].

$$\mu_A : x \in X \rightarrow [0,1]$$

Larger values of μ_A (*i.e.* those close to unity) denote higher degrees of fuzzy set membership. Membership values are not probabilities, and are not required to sum to unity.

The three basic fuzzy operations are generalisations of the complement, union and intersection operations for crisp sets, and the standard formulae for these operations are:

Complement	$\mu_{\bar{A}} = 1 - \mu_A$
Union (OR)	$\mu_{A \cup B} = \max[\mu_A, \mu_B]$
Intersection (AND)	$\mu_{A \cap B} = \min[\mu_A, \mu_B]$

If membership grades are restricted to $\{0,1\}$, these operations are identical to their crisp set counterparts. However, the axioms which underpin these fuzzy operations are not as stringent as their classical counterparts, and formulae other than the standard ones given above can be defined for the three basic operations (Klir and Yuan, 1995). Many such formulae have been proposed for various specialist applications.

The maximum and minimum functions are used as the standard fuzzy OR and AND operators respectively. The minimum function is also used as the standard fuzzy implication operator (THEN). A summation is used to aggregate the output fuzzy sets, and the resulting single membership function is defuzzified by calculating its centroid. Jang and Gulley (1997) discuss other possible AND, OR, implication, aggregation and defuzzification methods.

3.4.2 Fuzzy Aggregation Methods

Following Klir and Yuan (1995), a general fuzzy aggregation function, h^{fuzzy}, combines two or more fuzzy sets to produce a single fuzzy set, so that $h^{fuzzy} : [0,1]^n \rightarrow [0,1]$. Applied to n fuzzy sets, $A_1, A_2, \ldots A_n$, the aggregation function produces an aggregate fuzzy set, A, by operating on the membership functions of each set, so that:

$$\mu_A(x) = h^{fuzzy}[\mu_{A_1}(x), \mu_{A_2}(x), \ldots, \mu_{A_n}(x)] \;\; \forall \; x \in X$$

Fuzzy aggregation methods in general form a spectrum comprising intersection, averaging, and union operations. Most applications employ the standard forms of the intersection and union operations, namely the minimum and maximum functions. However, fuzzy union and intersection operators can be defined which produce values which are respectively greater than the maximum operation, and smaller than the minimum operation.

The Yager operators provide an example of such non-standard operators, and are defined as follows:

$$\begin{aligned} u_{Yager}(a,b) &= \min[1,(a^w+b^w)^{-w}] \\ &= u_{\max}[a,b] && w \to 0 \\ &= \max[a,b] && w \to \infty \end{aligned}$$

$$\begin{aligned} i_{Yager}(a,b) &= 1-\min[1,\{(1-a)^w+(1+b)^w\}^{-w}] \\ &= i_{\min}[a,b] && w \to 0 \\ &= \min[a,b] && w \to \infty \end{aligned}$$

such that $\max(a,b) \le u_{Yager}(a,b) \le u_{\max}(a,b)$

and $i_{\max}(a,b) \le i_{Yager}(a,b) \le \min(a,b)$.

The values i_{min}, and u_{max}, are respectively known as the drastic intersection and the drastic union, and define the lower and upper ends of the spectrum of fuzzy aggregation methods.

$$i_{\min}(a,b) = \begin{cases} a & \text{when } b=1 \\ b & \text{when } a=1 \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad u_{\max}(a,b) = \begin{cases} a & \text{when } b=0 \\ b & \text{when } a=0 \\ 1 & \text{otherwise} \end{cases}$$

Figure 3.2 shows the spectrum of fuzzy aggregation methods.

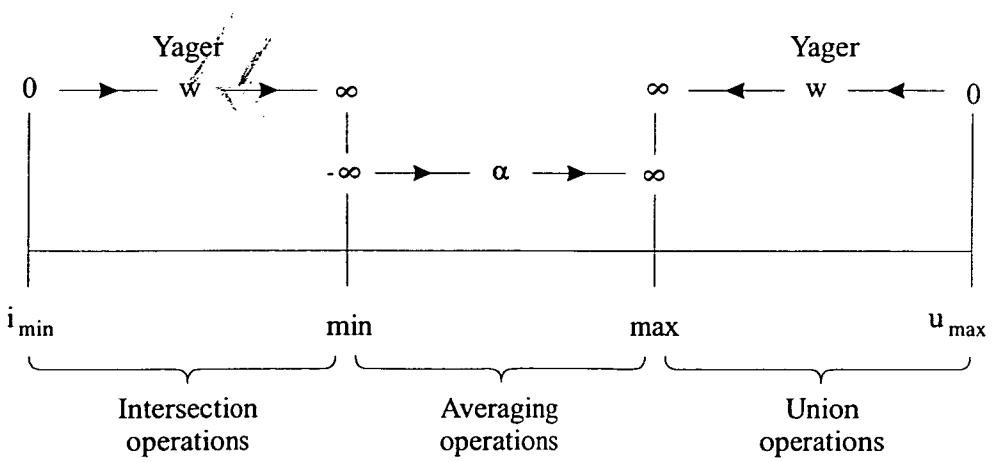


Figure 3.2 The spectrum of fuzzy aggregation operations (after Klir and Yuan, 1995).

The end ranges consist of non-standard intersection and union operations (the Yager operators are shown as an example), which respectively vary between the drastic intersection and the standard minimum operation; and the drastic union and the standard maximum operation. The middle range is occupied by fuzzy versions of the averaging functions, h_α, outlined in Section 3.2.

3.5 Case Study: Roadside Vegetation Quality Index

3.5.1 Introduction

Roadsides are often the only places where native vegetation remains in a region, and roadside management is a major concern of transport authorities and land care groups (VRCAC 1995; Palmar and Lewis 1987). A credible and simple roadside vegetation quality index offers an important way to determine roadside management priorities, and to monitor the effectiveness of management strategies. This case study examines traditional and expert system approaches to producing a roadside vegetation quality index.

3.5.2 Classical Approach

Vegetation quality indices developed to date assign scores to variables such as roadside width, and the condition of native vegetation, and then sum the scores. A high total score denotes a roadside with high vegetation conservation value, and a low total score denotes a highly degraded roadside. These scoring methods are crude, and fail to properly describe the relationships between input variables. To illustrate the problem, consider an index developed by the New South Wales Roadside Environment Committee (NSWREC, 1995). Table 3.2 shows the components of this index, omitting a score for the roadside's potential as a fauna habitat in order to focus on the vegetation quality.

Width of road reserve		**Condition of native vegetation**	
Unfenced	0	Degraded	1
1-5 m	1	Modified	2
6-21 m	2	Near natural	3
21+ m	3		
Extent of weeds		**Young trees or shrubs**	
Dominant	0	None	0
Scattered throughout	1	Moderate	1
Isolated clumps	2	Extensive	2
Few or none	4		

Table 3.2 Components of the NSWREC (1995) roadside vegetation quality index.

In calculating this index, roadside widths of 1-5 m score 1, while widths of 6-21 m score 2, so that a 21 m wide roadside scores only 1 point more than a 1 m wide roadside. In addition, the calculation does not take into account linkages between variables whereby, for example, a roadside with good condition native vegetation is not likely to have extensive weed infestation.

3.5.3 Expert System Approach

An expert system which uses fuzzy rules to aggregate the vegetation quality indicators into an index offers a way to better capture relationships between the variables, and the method also provides a smoother output than the traditional scoring method. The fuzzy rules reflect a more natural way of thinking about the problem, and there is no added complexity to the approach, since the input variables are the same as those used by the scoring method. The MATLAB software package was used to develop the fuzzy rule system described below, and Jang and Gulley (1997), and Cox (1994), detail programming methods.

Table 3.3 lists the fuzzy variables and their membership functions. The first four inputs are those used by NSWREC (1995), and the fifth input, *species,* describes the degree to which the native vegetation is protected by threatened species legislation.

	Name	Membership functions
Inputs		
Road reserve width	*Width*	*VThin, Thin, Medium, Wide, VWide*
Native vegetation condition	*Native*	*VDegraded, Degraded, Modified, Natural, VNatural*
Extent of weeds	*Weeds*	*VLots, Lots, Some, Few, VFew*
Young trees and bushes	*Regen*	*VFew, Few, Some, Lots, VLots*
Extent of threatened species	*Species*	*Threatened*
Output		
Vegetation quality index	*Index*	*VLow, Low, Medium, High, VHigh* and *Legal*

Table 3.3 Variables and membership functions for the expert system based index.

Figure 3.3 shows the five membership functions used to fuzzify the variable *width*. The functions *Thin, Medium* and *Wide* are Gaussian functions, while the functions *VThin* and *VWide* are falling and rising sigmoidal functions respectively. The input value is a crisp number between 0 and 10 (*e.g.* 3.5), and the corresponding membership function values denote the extent (on a scale of 0 to 1) to which the values satisfy the functions.

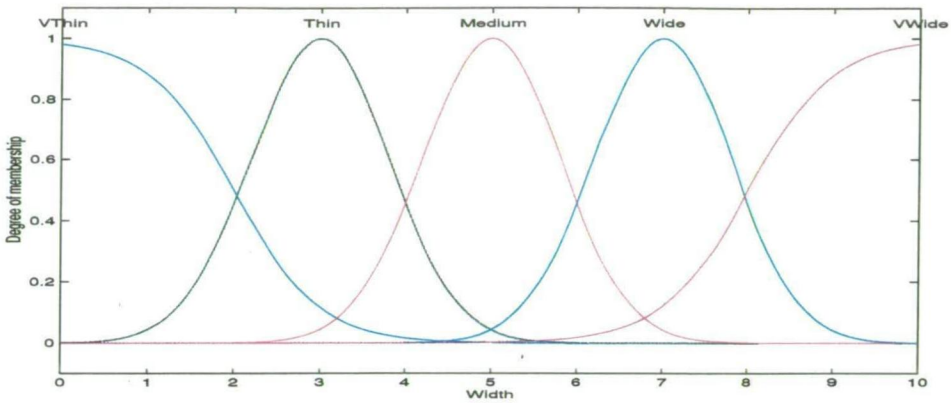


Figure 3.3 Membership functions for the variable *width*, comprising two sigmoidal end functions, and three Gaussian middle functions.

Similar membership functions are used for the other variables listed in Table 3.3. The input variables *width, native, weeds* and *regen* each have three Gaussian membership functions, plus falling and rising sigmoidal functions. The input variable *species* has a single sigmoidal function, *threatened*, which rises from 0 to 1 across the range 0 to 10. The output variable, *index*, has six membership functions: three Gaussian membership functions, falling and rising 'bookend' sigmoidal functions, and a third sigmoidal function, *legal*, which is used in the fuzzy rule involving the variable *species*.

To show how a expert system based on fuzzy rules works, consider three simple (illustrative only) rules involving the input variables *width, native* and *species*.

If (*Width* is *VThin*) OR (*Native* is *Degraded*) THEN (*Index* is *VLow*)
If (*Width* is *Thin*) AND (*Native* is *Modified*) THEN (*Index* is *Low*)
If (*Species* is *Threatened*) THEN (*Index* is *Legal*)

Figure 3.4 shows these rules applied to the input values of *width* = 1.5, *native* = 5 and *species* = 4. These inputs are numbers on a scale of 0 to 10, interpreted as Bad (0-2), Poor (2-4), Okay (4-6), Good (6-8), and Excellent (8-10), or similar descriptions. For example, the value *species* = 4 says that the roadside vegetation rates 4 out of 10 (Poor/Okay) in terms of the extent to which the various plants are protected by threatened species legislation.

The expert system first fuzzifies the three crisp input values, determining the extent (0 to 1) to which each input value satisfies the membership functions specified in the various rules. The system then evaluates the value (again 0 to 1) of that part of the fuzzy rule expression prior to the THEN operator, using the maximum and minimum functions as the fuzzy OR and AND operators respectively.

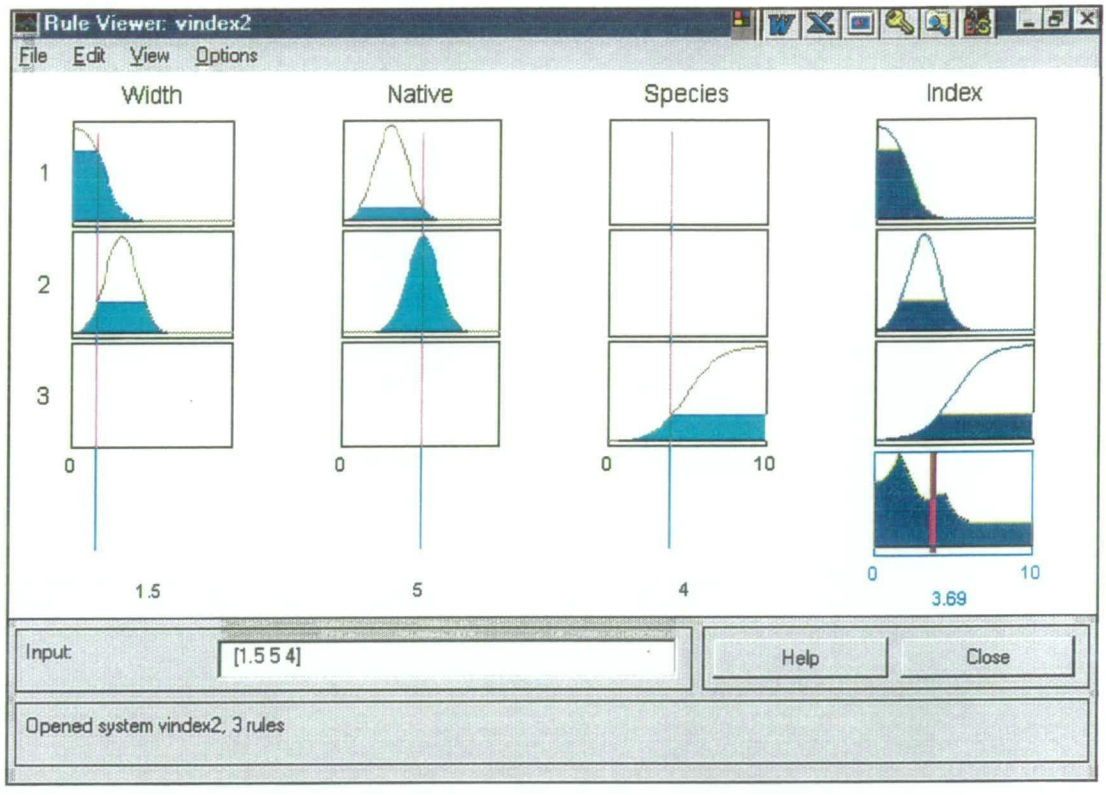


Figure 3.4 Three simple fuzzy rules in action. Similar membership functions are used for the three input variables and the output variable, but this is not a requirement.

For the first rule, the value of *Width* = 1.5 produces a *VThin* membership function value of 0.6225, while the value of *Native* = 5 produces a *Degraded* membership function value of 0.1353. The maximum function is used as the OR operator, so the value of the expression (*Width* is *VThin*) OR (*Native* is *Degraded*) is 0.6225, since 0.6225 is bigger than 0.1353.

For the second rule, the value of *Width* = 5 produces a *Thin* membership function value of 0.3247, while the value of *Native* = 5 produces a *Modified* membership function value of 1.0000 (i.e. a value of *Native* = 5 fully satisfies the *Modified* membership function). The minimum function is used as the AND operator, so the value of the expression (*Width* is *Thin*) AND (*Native* is *Modified*) is 0.3247, since 0.3247 is smaller than 1.0000.

For the third rule, the value of *Species* = 4 produces a *Threatened* membership function value of 0.2689, and this is the value of the expression (*Species* is *Threatened*).

Now that the inputs have been fuzzified, and the left hand side of each rule has been evaluated, the right hand side of each rule must be calculated. This is done by using the minimum function as the fuzzy implication (THEN) operator, which essentially chops off the top of each right-hand membership function at the value of the left-hand part of the fuzzy

rule. The fuzzy rules defined above involve three membership functions for the output, *Index,* namely *VLow, Low* and *Legal.* The right-hand column of Figure 3 shows these functions truncated at the values *VLow* = 0.6225, *Low* = 0.3247 and *Legal* = 0.2689.

Finally, a summation is used to aggregate the three rule outputs into a single membership function, which is shown in the bottom right panel of Figure 3.4. This aggregate membership function is defuzzified by calculating its centroid, to recover a crisp output value of 3.69.

The defuzzified output is specified to have a range between 0 and 10 (it could be anything, but this range is convenient since it can be interpreted using the usual Bad (0-2) through to Excellent (8-10) scale). In practice, the defuzzification method of taking the centroid of the aggregated membership function means that the lowest and highest possible values produced by a given set of fuzzy rules are, respectively, slightly higher than 0, and slightly less than 10. However, these limit values (1.6 and 9.3, say) can easily be used to scale the index value to the required output range.

3.5.4 Application to the Midland Highway

The set of fuzzy rules to replicate the traditional vegetation quality index is straightforward, since the rules do not need to explicitly take into account possible interactions between the variables.

If (*Width* is *VThin*) then (*Index* is *VLow*)
If (*Native* is *VDegraded*) then (*Index* is *VLow*)
If (*Weeds* is *VLots*) then (*Index* is *VLow*)
If (*Regen* is *VFew*) then (*Index* is *VLow*)
.
.
Similar rules for *Index* membership functions *Low, Medium* and *High*
.
.
If (*Width* is *VWide*) then (*Index* is *VHigh*)
If (*Native* is *VNatural*) then (*Index* is *VHigh*)
If (*Weeds* is *VFew*) then (*Index* is *VHigh*)
If (*Regen* is *VLots*) then (*Index* is *VHigh*)

A typical set of input values would be {*width, native, weeds, regen*} = {2.5, 7, 2, 6.5}, which are simply numbers between 0 and 10, interpreted as Bad (0-2) through to Excellent (8-10), or similar descriptions. As before, the crisp output value is calculated by the use of the centroid method of defuzzification, and this value is then scaled so that the lowest and

highest possible output values define some convenient range. To achieve correspondence with the NSWREC (1995) index, this output range is set to 1-12.

Figure 3.5 shows how the index calculated by the expert system varies with the inputs *width* and *native,* with the other inputs fixed at prescribed values. The smooth nature of the surface, termed a decision surface, gives confidence that the underlying rules are sensible.

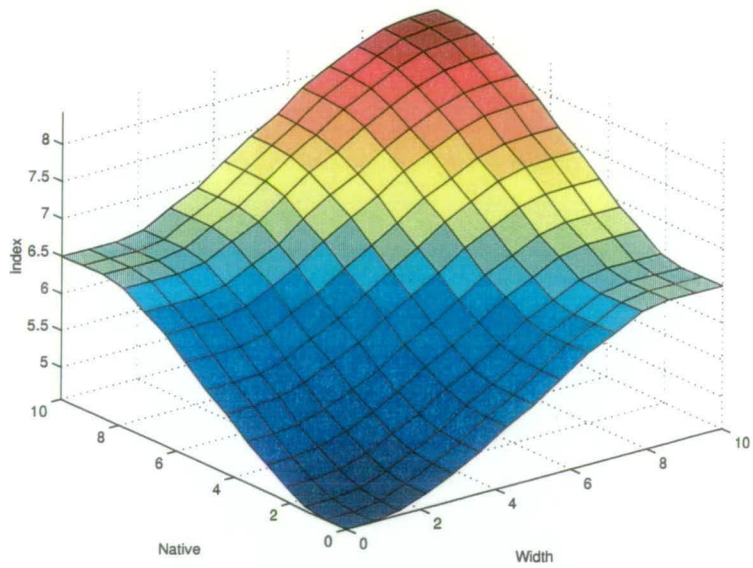


Figure 3.5 Dependence of the vegetation index (1-12) on input variables *width* and *native.*

A concern is that different sets of expert rules might be specified by different vegetation quality experts. However, experience suggests that sensibly conceived alternative sets of expert rules usually result in similar decisions, an observation which is supported by both the case studies presented herein.

Many other changes to the expert system are possible. For example,

- a different number of membership functions might be prescribed for some of the variables, for example the variable *width* might be described by the three membership functions *Thin, Medium* and *Wide,* instead of the five functions used above;
- different membership functions might be specified, for example triangular or trapezoidal functions might be preferred to the Gaussian and sigmoidal functions; or
- the expert rules might be weighted (the default is that the rules are equally weighted).

Again, experience suggests that calculations made by expert systems are fairly robust with respect to such changes. In other words, changes such as those suggested above do not usually make a big difference to the calculation.

Nevertheless, there is no guarantee that a fuzzy rule system will perform satisfactorily, and it must be tested against data. To test the above system, consider a section of the Midland Highway near Tunbridge in central Tasmania. Botanical surveys commissioned by the Department of Transport (*e.g.* North and Mallick, 1998) have determined that this stretch of highway has roadside vegetation with high conservation value. Survey data are recorded in an environmental database developed by the Department of Transport, assisted by consultants (*e.g.* Carter, 1996).

Table 3.4 shows the values of the four input variables for eight roadside sections, based on the Department of Transport's survey data. The roadside sections comprised four east and four west road sides, each 500 m long and spanning a 2 km distance from the start of link 55. The values were assigned using a scale of 0-10, divided into the usual 2-point ranges of Bad (0-2) through to Excellent (8-10). Table 3.4 also shows the vegetation quality index values using the NSWREC (1995) method, calculated by assigning the various input values an appropriate score according to Table 3.2, and presents the corresponding index values calculated by the expert system. Both sets of index values range from 1 to 12.

	Inputs (0 = worst, 10 = best)				**Vegetation quality indices**	
Section	***Width***	***Native***	***Weeds***	***Regen***	**Classical**	**Expert system**
East 1	4	5	4	5	6	6.1
East 2	4	5	5	5	6	6.1
East 3	4	2	8	4	7	6.4
East 4	9	5	6	5	9	7.2
East 5	2	0	5	0	3	1.8
West 1	4	5	3	7	7	7.9
West 2	4	2	6	4	7	7.2
West 3	4	9	2	6	7	7.2
West 4	4	7	3	7	6	6.1
West 5	2	1	4	0	3	2.2

Table 3.4 Vegetation quality index values (1-12) for the Midland Highway at Tunbridge.

The two index calculation methods agree well. There is a slight discrepancy between the two calculations for sections East 4, East 5 and West 5, but the Department of Transport's roadside vegetation specialist, Mr Jed Gillian, believes that the values calculated by the expert system better reflect the underpinning input data (see Carter and Gillian, 1998).

An obvious extension of the expert system is to add the input variable *species,* introduced previously, to take into account the presence or absence of vegetation protected by threatened species legislation. As before, the additional rule involving the new input is simply:

If (*Species* is *Threatened*) then (*Index* is *Legal*)

Where *Species* is the new input variable, fuzzified using a single sigmoidal membership function *Threatened,* and *Legal* is an additional (sigmoidal) membership function for the output *Index.* The new input is deemed to be more important than the first four inputs in determining the conservation significance of the roadside vegetation, and the additional rule is thus weighted by a factor of 3 compared to the other input variables.

Figure 3.6 shows the colour-coded index values, calculated by the extended system, applied to a map of the Midlands Highway. The index output range has been rescaled to 0-10 (rather than 1-12), for ease of interpretation. The revised index values closely correspond to the expectations of the Department of Transport's roadside vegetation specialist, Mr Jed Gillian, based on the comprehensive survey data provided by North and Mallick (1998).

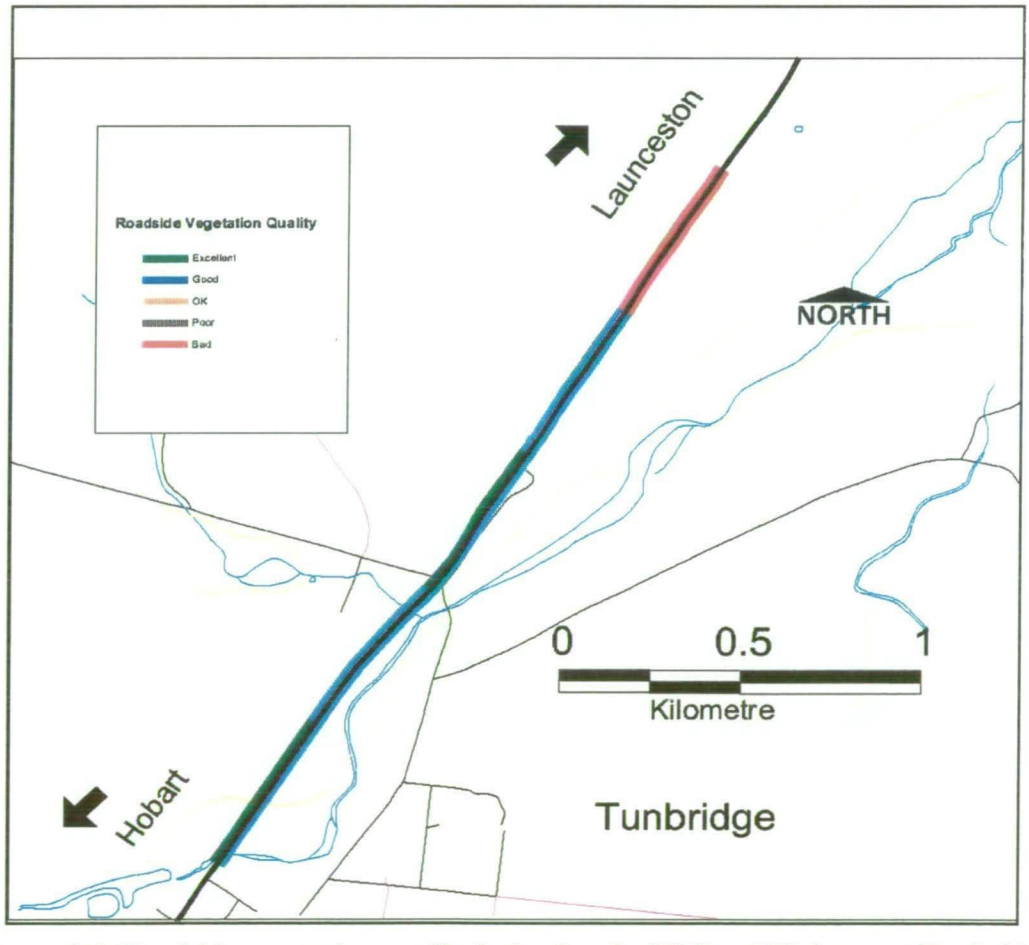


Figure 3.6 Roadside vegetation quality index for the Midland Highway at Tunbridge.

Table 3.5 shows the *Species* values for the eight roadside sections of the Midlands Highway, and also shows the new index values.

Section	*Species*	Revised Index	Rounded	Interpretation
East 1	8	7.02	7	Good
East 2	7	6.93	7	Good
East 3	6	7.01	7	Good
East 4	7	6.43	6	Good
East 5	0	0.69	1	Bad
West 1	9	8.05	8	Excellent
West 2	4	7.49	7	Good
West 3	9	7.59	8	Excellent
West 4	8	6.74	7	Good
West 5	0	1.06	1	Bad

Table 3.5 Revised vegetation quality index values (0-10), including a variable to take into account the conservation significance of any rare plants (0=none, 10 = lots).

Alternative expert rules

The following set of rules was examined as an alternative to the above expert system:

If (Width is Thin) or (Native is Degraded) or (Weeds is Lots) then (Index is VLow)

If (Weeds is Some) or (Regen is Few) then (Index is Low)

If (Width is Medium) or (Native is Modified) or (Weeds is Few) or (Regen is Some) then (Index is Medium)

If (Width is Wide) or (Regen is Lots) then (Index is High)

If (Native is Natural) then (Index is VHigh)

If (Species is Threatened) then (Index is Legal)

This alternative rule set uses fewer membership functions to fuzzify the input variables (for example, input *Width* only has three membership functions *Thin, Medium* and *Wide*), and the rule involving the input *Species* is not weighted. However, this set of rules produces almost identical results to those presented above, which supports the earlier assertion that sensibly conceived different sets of rules can produce similar results.

3.6 Case Study: Huon Estuary Algal Bloom Prediction

3.6.1 Introduction

The Huon estuary in southern Tasmania has developed into a center of commercial shellfish (abalone, oysters and mussels) and Atlantic salmon farming operations. Figure 3.7 shows the estuary, which is about 40 km long, together with the location of its fish farms. The adjacent land is primarily used for agriculture and forestry operations, with about 11,000 people living in the catchment area.

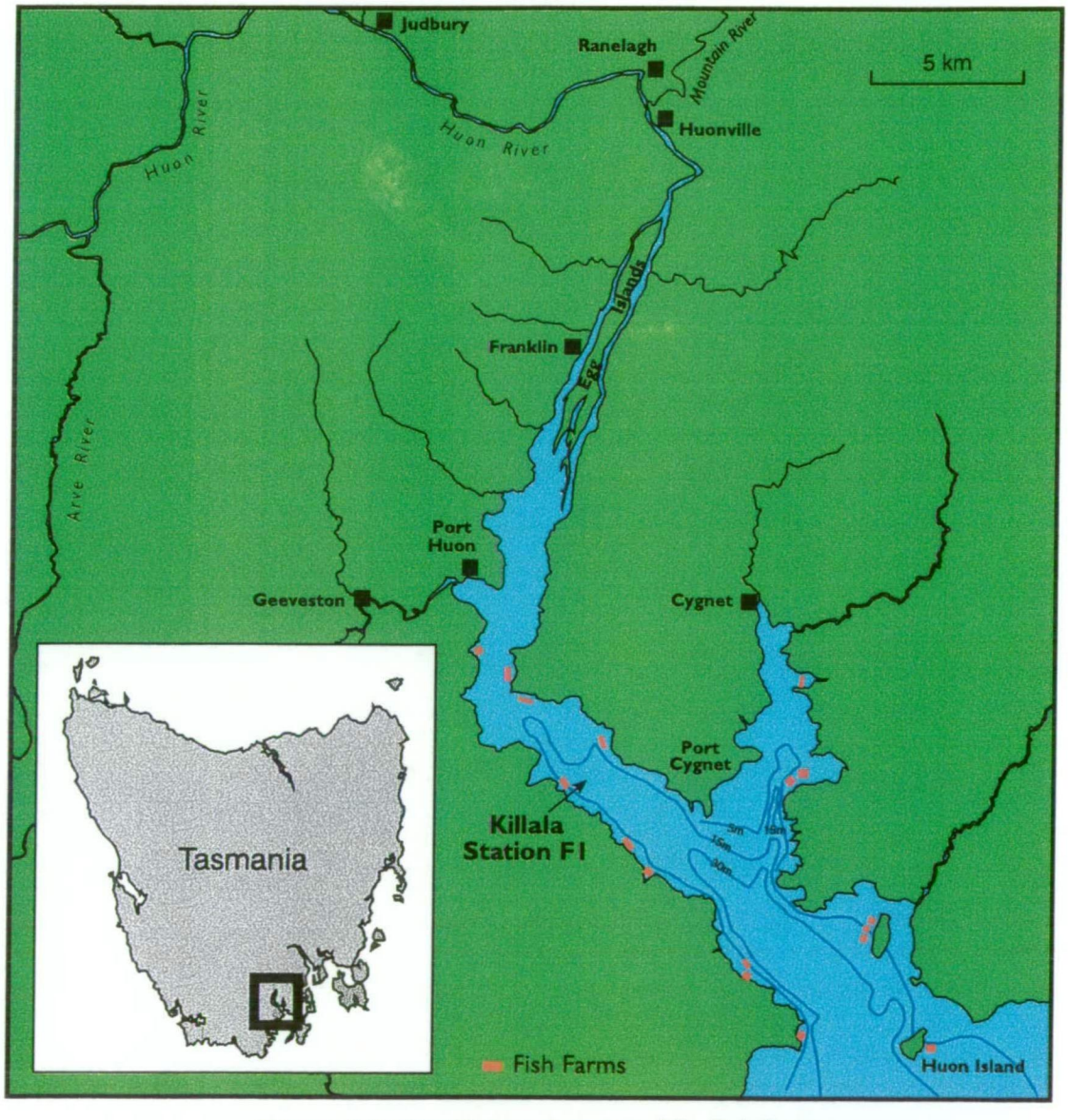


Figure 3.7 The Huon estuary and its fish farms.

The estuary is prone to algal (phytoplankton) blooms, and blooms of the toxic dinoflagellate *Gymnodinium catenatum* have cause occasional closure of shellfish farms for up to six months. Algal blooms are natural phenomena, and nutrients play a key role in sustaining

aquatic ecosystems, but there is evidence that bloom frequency and persistence can be intensified by nutrient enrichment (eutrophication) from sources such as agricultural practices or fish farming (Folke et al., 1994; Gilbert et al., 1997).

Fish farm production in the Huon estuary is expected to significantly increase in the next five years, and a major research program is being carried out to investigate natural estuarine processes, and how human activities can influence these processes. The three year program started in 1996, and is a joint project by the CSIRO Division of Marine Research and the Fisheries Research Development Corporation, assisted by several other organisations. The project background is given in DPIF (1994). One project goal is to determine the nutrient budget and algal dynamics in the estuary, and to predict the circumstances under which algal blooms can be expected. Generalisations from similar studies carried out on other estuaries are difficult since estuary dynamics are complex, and driven by a range of anthropogenic and natural pressures.

The research is supported by an extensive field work campaign to gather data on estuary biology, chemistry and physics. The campaign involves some 60 survey stations that are sampled quarterly, five stations that are sampled weekly, and two automatic stations.

3.6.2 Bloom Indicators

Table 3.6 sets out the principal *G. catenatum* bloom initiation variables at Killala Bay survey station (Figure 3.7), as identified by CSIRO microalgal biologists Dr Susan Blackburn and Ms Naomi Parker. An automated monitoring system was installed at Killala Bay on 31 July 1997, and data from this station to June 1998 is now available.

The runoff and water salinity measurements are partial surrogates for macro-nutrient and micro-nutrient concentrations (*e.g.* phosphates, and some trace metals such as selenium), which is important since these nutrients are probably crucial to bloom initiation. A number of other variables, notably wind speed and dissolved oxygen, are known to play roles in bloom initiation, but either data for these variables are not readily available, or their roles are only poorly understood. For example, strong winds of short duration will mix bottom sediments into the water column, and may help to initiate a bloom several weeks later. However, Hallegraeff et al. (1995) suggest that wind speeds of < 5 m/s for a period of at least 5 days are needed to ensure a sufficiently stable water column for bloom initiation.

Water temperature (°C)
Algal blooms correlate strongly with surface water temperature. *G. catenatum* bloom initiation appears to require temperatures exceeding 12 °C.

Runoff (m^3/s)
Hallegraeff et al. (1995) note that a rainfall event contributes nutrients from land runoff, and that there is a significant correlation between rainfall and Huon river flow. They suggest the need for a flow rate exceeding 100,000 ML over a 3 week period, measured at Frying Pan Creek.

Salinity of surface water (‰)
CSIRO has determined that bloom initiation at Killala station is most commonly associated with salinities of 20-22 ‰. Bloom initiation is contra-indicated by lower or higher salinities.

Secchi depth (m)
Secchi depth is a measure of water clarity. Bloom initiation is often associated with secchi depths less than about 2 m.

Water column stratification (surface - deep water salinity difference, ‰)
Bloom initiation is associated with a well stratified water column, and is contra-indicated by a well mixed water column.

Table 3.6 Variables influencing the initiation of *C. catenatum* blooms.

It was decided to use the three-week average flow rate, the secchi depth, the surface water salinity, and estuary stratification as algal bloom predictor variables. The average flow rate was calculated as the running mean of only three daily (24 hour average) measurements, one on the date of interest, and one from each of the two previous weeks. Estuary stratification was determined by examining the difference between surface and deep water salinity measurements, with little difference indicating a well mixed estuary, and significant difference indicating the presence of a well defined salt water wedge underlying the fresh water surface layer.

These inputs are clearly less than ideal, and have been selected by considering "best fit" conditions that will not always apply. For example, flow rates in the estuary are storm-event driven, and can vary by over 100 cumecs from day to day, which results in the calculated three week flow average being only a crude approximation to the actual three week mean. However, the variables listed in Table 3.6 are readily measured, and an algal bloom prediction method based on these variables could be of practical value to fish farm operators.

3.6.3 Expert Fuzzy Rule System

An expert fuzzy rule system was developed to predict the cell counts/L of *G. catenatum* measured at Killala Bay station, based on advice from Dr Blackburn and Ms Parker, and

using the MATLAB software package (Jang and Gulley, 1997). Two versions of the model were developed, with different surface salinity membership functions and associated rules. Model 1 corresponds to bloom initiation conditions associated with the Killala Bay station, while model 2 corresponds to bloom initiation conditions associated with the opposite side of the estuary, known as Wheatleys. Dr Blackburn and Ms Parker advised that algal blooms in these two locations were associated with significantly different optimum salinities.

Table 3.7 lists the membership functions used to fuzzify the four input variables and the bloom count output.

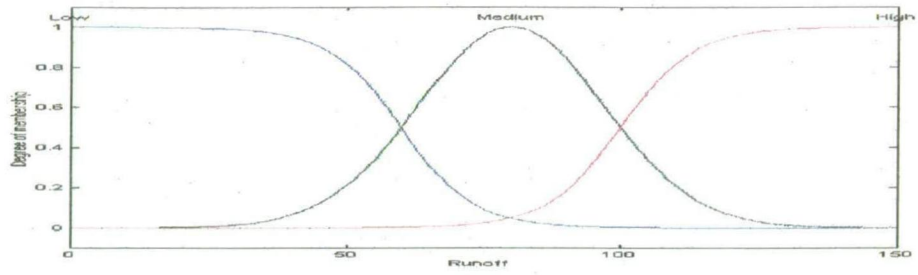
Variable	Name	Membership functions
Inputs		
3 week average flow	*Runoff*	*Low, Medium, High*
Surface water salinity	*SurfSal model 1*	*VeryLow, Low, Optimum, High, VeryHigh*
	SurfSal model 2	*VeryLow, Low, Optimum, High*
Secchi depth	*Secchi*	*Low, Medium, High*
Estuary stratification	*DeltaSal*	*Mixed, Medium, Stratified*
Output		
G. catenatum count.	*Count*	*Low, Medium, High*

Table 3.7 Input and output variables and their membership functions.

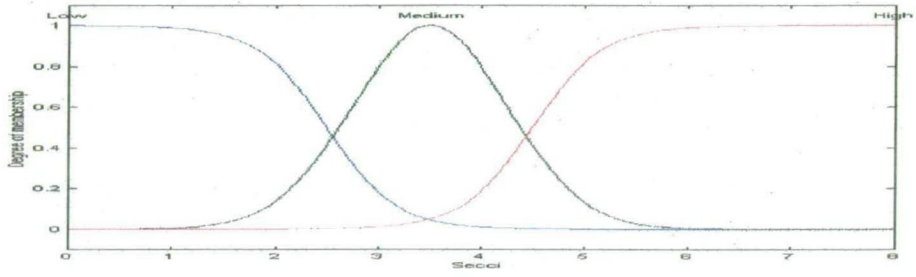
The membership functions are shown in Figures 3.8 and 3.9. In the case of Model 2, the salinities were best represented by trapezoidal membership functions, due to the asymmetric nature of the salinity ranges specified for the rules.

Table 3.8 gives the rules used by the two models. Considering the output, a *G. catenatum* count of less than 10,000 cells/L is reported as No Bloom, a count of between 10,000 and 100,000 cells/L is considered to be a Partial Bloom, and counts higher than 100,000 cells/L correspond to a Major Bloom. Signs of *G. catenatum* toxicity in shellfish are associated with cell counts higher than about 10,000 cells/L (DPIF, 1994).

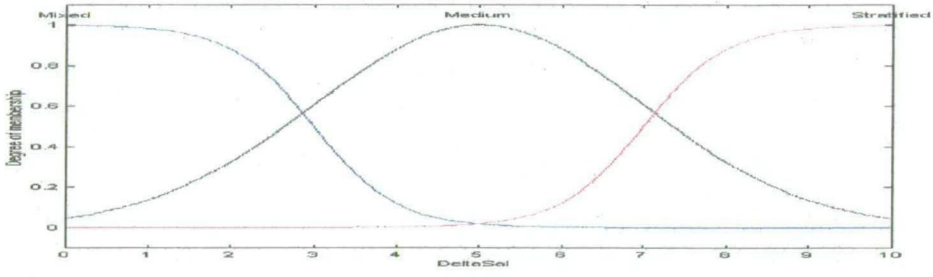
The membership functions used to fuzzify the algal bloom count only span the range of 0 to 150,000 cells/L, in order to properly describe predictions of low counts. The highest cell count recorded to date at Killala Bay station is 495,000 cells/L, and thus the expert system predictions were rescaled to the range 0 to 500,000 cells/L.



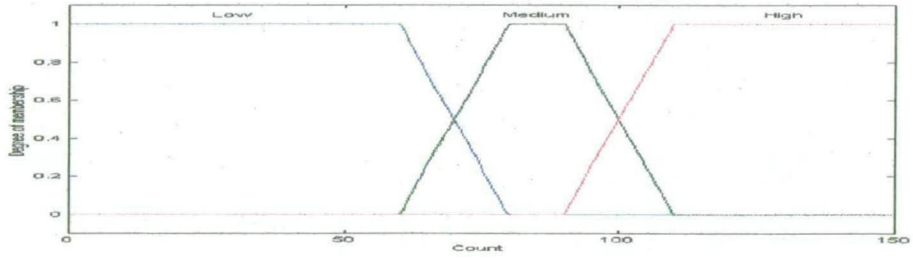
River flow (cumecs)



Secchi depth (m)

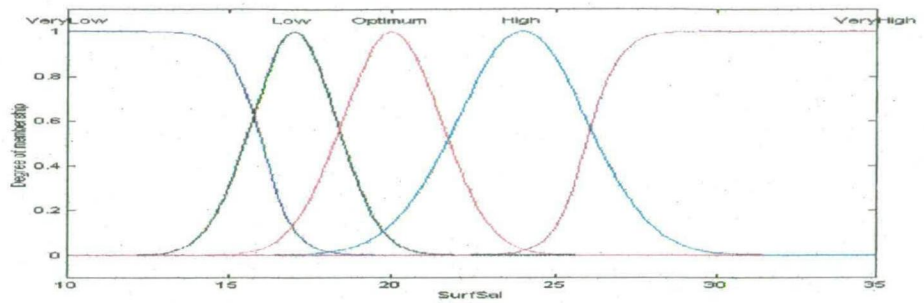


Estuary stratification, measured as surface-deep salinity (‰)

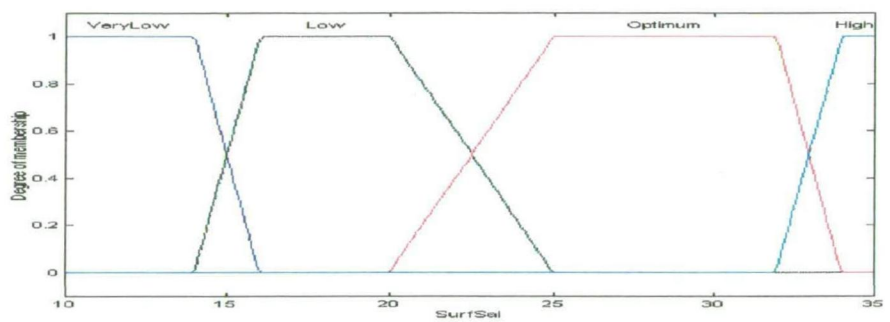


G. catenatum count (thousand cells/litre)

Figure 3.8 Membership functions common to both versions of the expert system.



Model 1.



Model 2.

Figure 3.9 Surface salinity membership functions.

Common rules
If (Runoff is Low) then (Count is Low)
If (Runoff is Medium) then (Count is Medium)
If (Runoff is High) then (Count is High)
If (Secchi is High) then (Count is Low)
If (Secchi is Medium) then (Count is Medium)
If (Secchi is Low) then (Count is High)
If (DeltaSal is Mixed) then (Count is Low)
If (DeltaSal is Medium) then (Count is Medium)
If (DeltaSal is Stratified) then (Count is High)

Model 1
If (SurfSal is VeryHigh) then (Count is Low)
If (SurfSal is High) then (Count is Medium)
If (SurfSal is Optimum) then (Count is High)
If (SurfSal is Low) then (Count is Medium)
If (SurfSal is VeryLow) then (Count is Low)

Model 2
If (SurfSal is High) then (Count is Low)
If (SurfSal is Optimum) then (Count is High)
If (SurfSal is Low) then (Count is Medium)
If (SurfSal is VeryLow) then (Count is Low)

Table 3.8 Fuzzy algal bloom prediction rules. All have equal weight.

The bloom prediction strategy was to first determine whether the rule sets associated with each of the four inputs agreed in their bloom prediction. For example, the rules associated with a low bloom count prediction are as follows:

(Runoff is Low)
(Secchi is Low)
(SurfSal is VeryLow) or (SurfSal is VeryHigh)
(DeltaSal is Mixed)

If the four input values fuzzified by these membership functions yielded memberships of at least, say, 0.45 (on the usual scale of 0 to 1), then agreement on a low count prediction was achieved, and the cell count prediction was made using all four input variables. However, if there was disagreement between the rules, then the average flow rate was discarded (as the least reliable predictor variable, given its crude calculation method), and the cell count prediction was made using the remaining three input variables.

Most of the measurements available from Killala Bay station were made during the warmer months of the year, and there is little point fuzzifying the water temperature measurements for use in the rule-based prediction system. However, a constraint was added to the expert system whereby a surface water temperature less than 12 ºC would produce a No Bloom prediction.

3.6.4 System Performance

The available data from Killala Bay station comprise weekly sets of measurements between 20 October 1997 and 6 May 1998. Table 3.9 summarises the data input to the expert system, excluding surface water temperature, and compares measured and predicted *G. catenatum* counts. The water temperature ranged from 12.5 ºC to 18.2 ºC, except for a measurement of 11.4 ºC on the 20 October 1997 (which triggers the automatic No Bloom prediction).

Table 3.9 colour-codes the bloom count predictions as No Bloom, Partial Bloom and Major Bloom. The models performances are similar when the predictions and measurements are compared in these terms (the No Bloom prediction for 20 October 1997 was determined by the low water temperature, not by the fuzzy rule system). In the case of model one, 13 *G. catenatum* cell count predictions agreed with observations, 5 predictions were of a Partial Bloom when the observation was either No Bloom or a Major Bloom; and 4 predictions were No Bloom or Major Bloom, when the opposite was observed.

Date	Flow (m^3/s)	Secchi (m)	SurfSal (‰)	DeltaSal (‰)	G.c. counts (thousand cells/L) Measured	Model 1	Model 2
20 Oct 97	179	1.5	26.2	8.3	0	0	0
27 Oct 97	169	5.5	33.7	0.9	2	6	9
11 Nov 97	85	4.5	29.3	5.5	1	70	119
9 Dec 97	21	2.5	25.5	9.3	132	446	392
16 Dec 97	74	3.5	34.8	0.0	118	47	75
30 Dec 97	80	4.0	28.9	5.9	231	104	181
6 Jan 97	78	7.0	32.1	2.6	119	26	39
13 Jan 98	19	3.0	31.6	3.7	495	316	239
23 Jan 98	10	6.0	32.9	2.0	41	12	16
27 Jan 98	8	6.5	32.6	1.8	35	11	15
3 Feb 98	9	5.0	34.6	0.3	0	1	2
9 Feb 98	39	4.5	34.0	0.8	0	6	8
24 Feb 98	70	2.5	30.0	4.7	0	153	298
3 Mar 98	75	5.0	32.8	2.1	2	21	32
10 Mar 98	48	2.5	30.0	4.9	0	155	302
17 Mar 98	20	5.0	34.7	0.2	0	1	1
24 Mar 98	18	4.5	34.6	0.2	2	1	2
7 Apr 98	20	6.0	33.1	1.7	7	9	13
14 Apr 98	137	4.0	33.1	1.7	3	43	65
21 Apr 98	141	5.0	31.1	3.8	11	47	76
28 Apr 98	138	6.5	34.0	0.4	133	2	4
6 May 98	27	4.5	34.4	0.4	196	2	3

	No Bloom	< 10,000 cells/L
	Partial Bloom	10,000 to 100,000 cells/L
	Major Bloom	> 100,000 cells/L

Table 3.9 Killala Bay survey data and *G. catenatum* measurements vs. predictions.

However, model 1 is preferred to model 2 when the predictions and measurements are compared using correlation coefficients. The measured *G. catenatum* cell counts and the model 1 predictions have a correlation coefficient of 0.52, while the correlation coefficient between the measured *G. catenatum* cell counts and the model 2 predictions is only 0.33.

3.7 Review and Conclusions

Chapter 2 concluded that sustainability is best quantified in terms of indicators, organised into biodiversity, socio-economic, and physical environmental themes. Each sustainability theme can be described either by an extended set of detailed indicators, or by a more concise set of fingerprint indicators, or by an index. These levels of detail form an information pyramid, with the apex of the pyramid corresponding to the highest degree of indicator aggregation.

This chapter examined classical and fuzzy rule system approaches to indicator aggregation for cases in which the relationships between the set of indicators and the index are reasonably well understood, at least to the extent that they can be described by a simple mathematical formula or articulated by experts as a set of rules. In some situations, a fuzzy rule system may prove to be a more elegant option than a traditional aggregation method. Of course, any set of fuzzy rules must be verified against test data.

This chapter presented two case studies. The roadside vegetation study introduced a fuzzy rule system which emulated a traditional scoring approach to calculating a vegetation quality index. The two systems used the same input variables, but the fuzzy rule system was shown to have a smoother decision surface, and it was shown how the system could easily be extended to capture relationships between variables.

The second case study used expert rules to predict algal cell counts. The performance of the fuzzy system was encouraging, given that a minimum number of inputs was used. A more detailed rule set would include factors such as wind speed, and bloom growth times. Also, the conditions for bloom sustenance are slightly different from those necessary for bloom initiation, and the present expert system does not take this into account. In other words, the system has no memory of its previous predictions, and could be improved in this regard.

However, the second case study was a complex prediction problem in which not all the relationships between the predictor variables and the target index are fully understood. This suggests that a pattern recognition approach to such problems might be better (although in the case of the Huon Estuary study, there is only a limited amount of data available on which to base such methods). Pattern recognition index methods are described in Chapter 4.

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4.0 INDICATOR AGGREGATION 2: PATTERN RECOGNITION METHODS

4.1 Introduction

Chapter 3 highlighted the importance of aggregation in producing indicators from raw data, or indices from sets of indicators, in order to simplify the description of sustainability issues associated with a project. The aggregation methods were appropriate for situations in which the relationships between the indicators and the index are fairly well understood. In such cases, classical aggregation functions can be applied, or experts can suggest rules upon which to base a fuzzy approach.

This chapter examines problems in which the relationships between a set of indicators and the index they support are not clear, even though it is obvious that such relationships exist. In such cases, it is appropriate to use an index method based on pattern recognition methods, principally either statistical techniques such as regression analysis, or neural networks.

4.2 Regression Analysis

Regression analysis is the main classical tool used to explore relationships that link a set of predictor variables (the indicators) to a response variable (the index). The use of a pattern recognition method such as regression analysis is triggered by lack of knowledge regarding the predictor-response relationships, and most regression analyses assume that the predictor-response relationships are linear. The validity of this assumption can be tested by examining bivariate scatterplots of the various indicators and the target index. Curvature of the scatterplot relationships indicates non-linearity, and a non-linear regression equation can be determined empirically.

Many texts on regression analysis have been written (*e.g.* Draper and Smith, 1966; Gunst and Mason, 1980; McPherson, 1990), and only relevant theory is summarised here. In both case studies, the *S-Plus* software package is used to carry out a multiple linear regression analysis of candidate predictor variables, and hence develop a regression model to forecast an index based on a small number of preferred predictor variables. *S-Plus* usage is described by MathSoft (1995), and by Venables and Ripley (1997).

Consider first the regression line for one predictor variable, x, and a response variable, y (*e.g.* Newland, 1975). In the simplest case, the variables are plotted as an x-y scatterplot which has its origin set at the "centre of gravity" of the data points. In other words, the variable means are zero: $E[x] = E[y] = 0$. A linear relationship is assumed, $y = mx$, and the average value of the square of the deviation, Δ, of any value from its predicted value is:

$$E\left[\Delta^2\right] = E\left[(y - mx)^2\right]$$

$$= E\left[y^2\right] + m^2 E\left[x^2\right] - 2mE[xy]$$

Minimising this by differentiation gives the optimum value of the slope, m. The regression line is then given by:

$$y = mx = \frac{E[xy]}{\sigma_x \sigma_y} x, \quad \text{or equivalently by } \frac{y}{\sigma_x} = \left\{\frac{E[xy]}{\sigma_x \sigma_y}\right\} \frac{x}{\sigma_y}$$

where (for zero means) the variances are $\sigma_x^2 = E\left[x^2\right]$ and $\sigma_y^2 = E\left[y^2\right]$.

The correlation coefficient is $R = \dfrac{E[xy]}{\sigma_x \sigma_y}$, and consistency of the line of regression of x on y with the line of regression of y on x requires that R = ± 1. The limit values indicate perfect direct or inverse correlation respectively.

For the case of non-zero means: $R = \dfrac{E[(x - m_x)(y - m_y)]}{\sigma_x \sigma_y}$.

Next, consider a multiple linear regression model which predicts a response, y, from a set of n predictor variables, $x_1, \ldots x_n$. This model has the form:

$$y_i = x_0 + \sum_{j=1}^{n} \alpha_{ij} x_j + \varepsilon_i$$

where the α_{ij} are weights applied to the predictor variables, and a residual, ε_i, is the difference between the ith observation and the predicted response, y_i. Since a model only approximates the real world, ε_i can be regarded as the observed error if the model is correct. The model generally performs better if the response values (and hence the residuals) are normally distributed with respect to the predictor variables used to construct the model.

As before, least squares minimisation of the residuals is used to fit the model to the predictor variables, using a baseline data set. The extent to which the model correctly predicts the response variable is assessed by analysing the variance of the predicted and measured response variable values. The smaller the variance, the better the prediction.

McPherson (1990) reviews variance characteristics. The basic identity in variance analysis is the total sum of squares, which comprises the regression sum of squares, plus the residual sum of squares:

$$i.e.\ \ \sum(Y_i - \bar{Y})^2 = \sum(Y_i' - \bar{Y})^2 + \sum(Y_i - Y_i')^2$$

This identity relates the n measured variables, Y_i, the n predicted response variables, Y_i', and the mean of the measured variables, $\bar{Y}$.

The R-square measure of variance is: $$R^2 = \frac{\text{Regression sum of squares}}{\text{Total sum of squares}} = \frac{\sum(Y_i' - \bar{Y})^2}{\sum(Y_i - \bar{Y})^2}.$$

R-square ranges from 0 to 1 in value. It is the square of the multiple correlation coefficient (the correlation between the observed and the predicted variables), and accordingly a value of R-square close to unity indicates that the model is a good fit of the data, and accounts for most of the variability of the predictor variables. Another way of interpreting R-square is that it is the proportion of variation in the target variable which is predictable from the best linear combination of predictor variables.

Testing the statistical significance of R-square provides a test of the linearity assumption which underpinned the regression analysis. One common test is based on computing the F-statistic:

$$F = \frac{u/d_u}{v/d_v}$$

The variables u and v are, in this case, both estimates of the same quantity (R-square), and so the F-statistic should have a value close to unity. Repeated sampling of u and v for different numbers of degrees of freedom leads to the F-distribution, which is the frequency distribution for the two variables in terms of their degrees of freedom. The distribution is given in many texts (*e.g.* McPherson, 1990), and is not repeated here.

The extent to which the F-statistic lies in the right-hand tail of the F-distribution for the two variables provides a measure of the statistical reliability of the R-square value. The tail-end region is usually defined as the highest 1% or 5% of F-values in the distribution, and in either case the critical value, F_0, can be obtained from tables given in terms of the d_u and d_v degrees of freedom (*e.g.* Hoel, 1947).

The S-plus software package uses an expression for the F-statistic given by Tabachnick and Fidell (1989):

$$F = \frac{R^2/k}{\left(1-R^2\right)/\left(n-k-1\right)}$$

where n is the number of data records, and k is the number of predictor variables. The value of F_0 is obtained from tables using k and $(n - k - 1)$ degrees of freedom. If $F > F_0$, then the R-square measure of variance is a reliable representation of the variables.

The F value can also be converted to a p-value, which is the probability that $F > F_0$. A p-value of more than 0.05 indicates strong support for the model. (The S-plus software package computes the quantity P = 1 - p, such that a low P value indicates a good model).

4.3 Neural Networks

4.3.1 Introduction

Neural network theory has its origins in the 1940s, the key idea being that a simple computing element can mimic a biological neuron (McCulloch and Pitts, 1943). Figure 4.1 shows the basic (artificial) neuron model. It was hoped that networks of neurons might function in a manner similar to a brain, and although these hopes have not yet eventuated, neural networks have been successfully applied to many problems in engineering and other fields. The history of neural networks is reviewed by Wasserman (1989), and Kosko (1992).

The input to the neuron shown in Figure 4.1 is termed its activation, X, which is the algebraic sum of n inputs, $\{x_1 \ldots x_n\}$, weighted by weights, $\{w_1 \ldots w_n\}$.

$$X = \sum_{i=0}^{n} w_i x_i$$

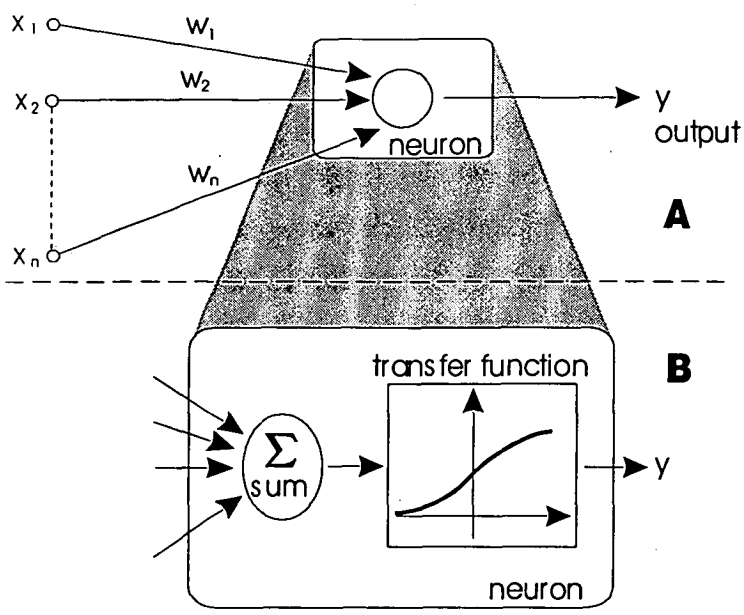


Figure 4.1 A: A single neuron with n inputs (x_1 to x_n), produces a scalar output, y. B: Inside the neuron, the sum of the inputs is passed to a transfer function, which produces the output.

A neuron is essentially a transfer function, F, which takes the activation, X, as its input, and produces a scalar output, Y. Figure 4.2 shows common transfer functions.

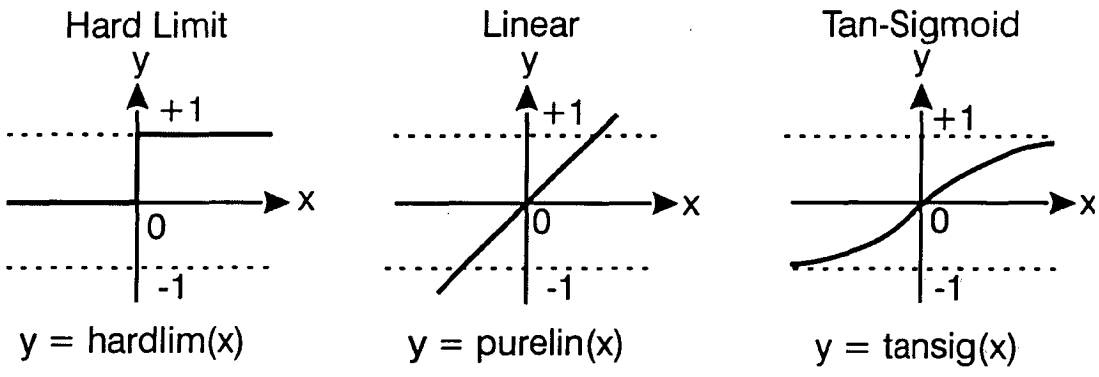


Figure 4.2 Common neuron transfer functions.

An additional input, termed a bias, x_0, is often added to the regular inputs, and weighted by an amount w_0. The bias can either be constant (typically unity) or adjustable, and allows a non-zero activation value to be passed to a transfer function, even when all the regular input values are zero.

4.3.2 Networks

A network of neurons can "learn" to produce appropriate responses to input data, by using a training algorithm to adjust the weights of the neurons according to the network's response to the input data. A trained network can produce sensible output when presented with new data (Rojas, 1996; Ripley 1996). Neural networks are ideal for discerning patterns in data, even when the patterns are non-linear, or the data are noisy.

A neural network is established as follows:

1. Define an appropriate network architecture.
2. Initialise the neuron weights and biases.
3. Define a training rule, and train the network.
4. Validate and apply the network.

A neural network consist of one or more layers of neurons, and a network's architecture is defined by number of neuron layers, the number of neurons in each layer, and the type of transfer function used by the neurons in each layer (all the neurons in a given layer are assumed to use the same transfer function).

Figure 4.3 shows a typical three-layer network.

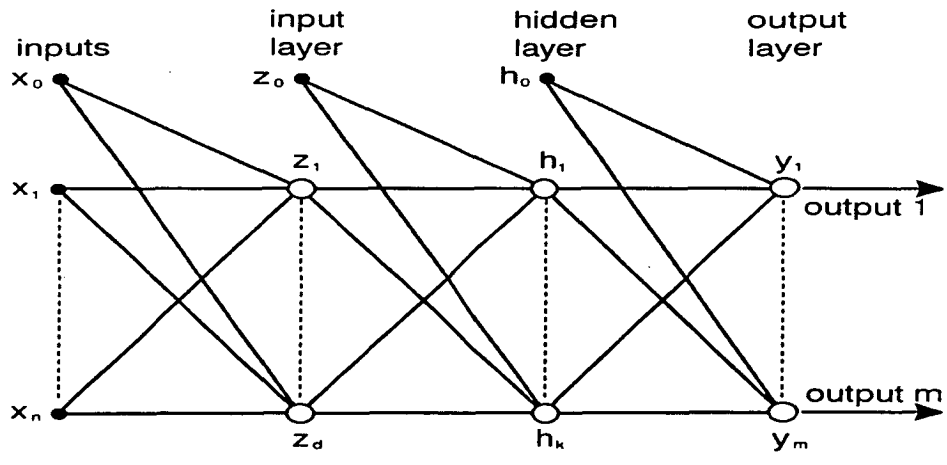


Figure 4.3 A three-layer neural network, including biases (weights not shown).

The n input values $\{x_1 \ldots x_n\}$ and a bias, x_0, are directed to the neurons in the first layer of the network, $\{z_1 \ldots z_d\}$, and there is no restriction on the number of neurons, d, in the input layer. Layers of neurons between the input layer and the output layer are termed hidden layers, and again there is no restriction on the number of neurons in these layers. In Figure 4.3, the single hidden layer has k neurons, $\{h_1 \ldots h_k\}$, and these neurons receive as their input the output from the d neurons of the input layer, plus a bias z_0.

The network's output layer has m neurons, $\{y_1 \ldots y_m\}$, where m is the number of required output values. In Figure 4.3, these m neurons receive as their input the output from the k neurons of the hidden layer, plus a bias h_0. In the case of an index method, the network is usually expected to produce a single output (the index) in response to a given set of inputs (the indicators), in which case the output layer will comprise a single neuron.

Neural networks can be classified as either feed-forward or feedback networks. Feed-forward networks contain no closed loops, and are well suited for pattern recognition applications, such as an index method. A feedback network is one in which the outputs are connected to its inputs, allowing the network to exhibit temporal behaviour (Kosko, 1992; Demuth and Beale, 1998).

For index method applications, a *supervised learning* algorithm is usually appropriate, and various algorithms are outlined below. The network can either be presented with each set of training inputs in turn, and the neuron weights adjusted in response to each output produced by the network; or else the learning algorithm may be based on the network's overall responses to a number of training indicator sets, which is known as batch learning.

Two other network training approaches are commonly used. In *unsupervised learning*, the network is trained without target data, for example to discover clusters of structure in the data. In *reinforcement learning*, the network outputs are judged simply to be bad or good, without supplying actual target values.

4.3.3 Perceptron and Linear Networks

The *perceptron* is a feedforward network of neurons that use a step transfer function to produce an output of either 0 or 1. The idea was developed by Widrow and Hoff (1960) based on work by Rosenblatt (1958). The perceptron's activation, X, and output, Y, are:

$$X = \sum_{i=0}^{n} w_i x_i \qquad \text{and } Y = \begin{cases} +1 & X \geq T \\ -1 & X < T \end{cases}$$

where T is the threshold for the step transfer function. The perceptron training rule adjusts neuron weights based on examples of correct behaviour, as follows:

$$\Delta w_{ij} = w_{ij}^{new} - w_{ij}^{old} = \varepsilon_i \, x_j$$

where w_{ij} is the weight associated with the input j to neuron i; $\varepsilon_i = t_i - Y_i$ is the error, with t_i being the correct (target) response . A perceptron network is only capable of training a single layer of neurons, but can separate any linearly separable set of vector data in a finite number of weight adjustments, or learning epochs (Rosenblatt, 1962). The training rule can be normalised to avoid insensitivity to very large or small inputs (Demuth and Beale, 1998)

A *linear network* uses neurons with linear transfer functions, which allows its output to be any value. Such networks can approximate linear functions, and can be used for pattern association problems in this regard. Consider a training data set containing n records, with each record consisting of an input vector x_i (the predictor variables), and the correct target response, t_i. The network's response is y_i, and sum-square error (SSE) is:

$$\text{SSE} = \sum_{i=1}^{n} (t_i - y_i)^2$$

The derivative of the mean SSE with respect to weight w_{ij} is (Zurada, 1992):

$$\frac{\partial SSE}{\partial w_{ij}} = -2\varepsilon_i x_j$$

The network is trained by computing all such derivatives, and adjusting the neuron weights to decrease (and eventually minimise) the mean SSE, the basic adjustment being:

$$\Delta w_{ij} = \eta\, \varepsilon_i\, x_j$$

This gradient descent approach can be based on different error functions, but the SSE is the most common (Bishop, 1995). The rule often referred to as the Delta rule, or the Widrow-Hoff rule (Widrow and Hoff, 1960). It is similar to the perceptron training rule, except for the use of a *learning rate*, η, which is a computation acceleration parameter (the technique is used elsewhere in numerical methods).

A linear network has an error surface which is a multi-dimensional parabola, each dimension corresponding to an input variable. There is only one (global) minimum, and thus the training rule minimises the network error even if a perfect solution does not exist. Once trained on a set of target vectors, the network can generalise to accept an input which

was not part of the training set, producing an output vector similar to similar input vectors. The training rule allows the network to adaptively track changes in the input/output vectors (Widrow and Sterns, 1985; Demuth and Beale, 1997).

4.3.4 Backpropagation Networks

Feed forward neural networks with hidden layers are often trained by *backpropagation* algorithms. These networks can approximate almost any function, and generalise to new data better than linear networks.

The backpropagation training approach overcame the problem of how to adjust neuron weights in the hidden layer in order to reduce the error in the network's output. As for the linear network training rule outlined above, backpropagation training is an error gradient descent method. The basic approach was popularised by Rumelhart and McClelland (1986), and many variations of the algorithm have subsequently been developed (Kosko, 1992).

Backpropagation is a two-step procedure, in which activity from the inputs flows forward through the various layers of neurons in the network, while the weight corrections flow backwards through the network (Caudill and Butler, 1994). The error gradient is calculated from the instantaneous errors in the responses of the output layer neurons, and the calculation of a gradient means that a network must use neurons with differentiable transfer functions. Sigmoidal functions are popular, and the basic sigmoidal function and its derivative are:

$$f(\alpha) = \frac{1}{1+e^{-\alpha}} \quad \text{and} \quad \frac{\partial f(\alpha)}{\partial \alpha} = f(\alpha)[1 - f(\alpha)].$$

The hidden layer neurons often use log-sigmoidal or tangent-sigmoidal transfer functions, while the output layer neurons usually use a linear transfer function.

The training rule is again a generalisation of the Delta rule, $\Delta w_{ij} = \eta E f(I)$, where:

$$E_j^{output} = t_j - Y_j \quad \text{and} \quad E_j^{hidden} = \frac{\partial f(I_i^{hidden})}{\partial I} . \sum_{j=1}^{n} \left(w_{ij} E_j^{output} \right).$$

In contrast to linear networks, the error surface of a backpropagation network can have local minima. The error gradient descent training approach thus may produce a set of network weights that corresponds to a local error minimum, and that may not be an acceptable solution. However, the use of an *adaptive learning rate* and/or *momentum* can help to avoid this problem (Kosko, 1992; Bishop, 1995; Ripley, 1996; Demuth and Beale, 1998).

An adaptive learning rate is one which is modified in response to changes in the local error surface. For example, if the network error at step *k* is less than the error at step *k-1*, then the learning rate might be increased; otherwise it might be decreased and the step repeated. However, White (1989) notes that the stochastic nature of backpropagation algorithms means that, while a small learning rate usually improves network stability, it does not guarantee convergence.

The momentum parameter, μ, is a (second) computation acceleration factor, that is proportional to the weight adjustment used in step *k-1*.

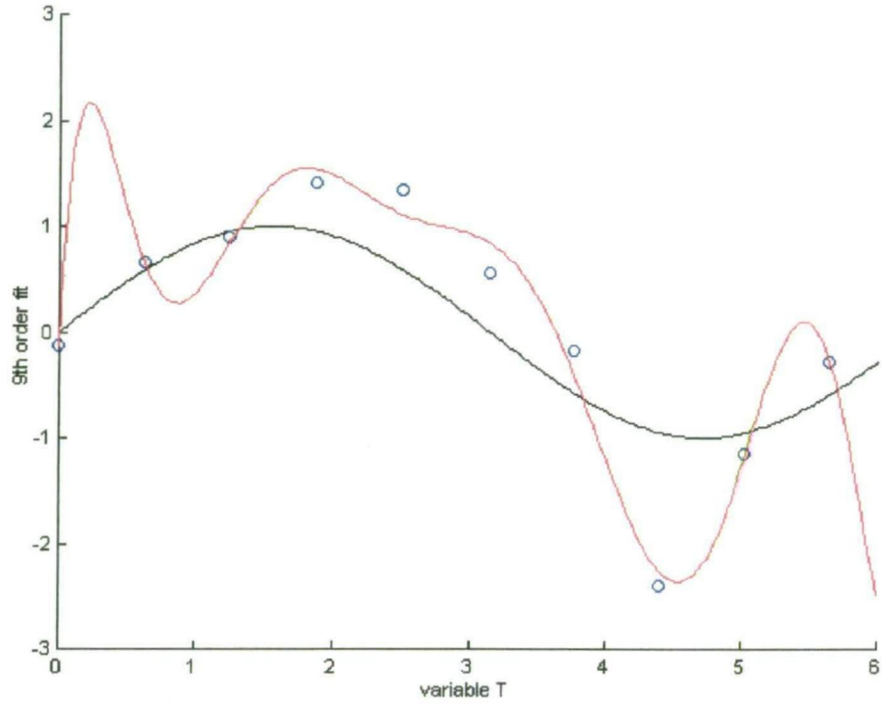
$$\Delta w_{ij}^{k} = \eta Ef(I)\big|^{k} + \mu \Delta w_{ij}^{k-1}$$

The momentum parameter usually varies between 0 and 1, and its effect is to smooth the local curvature of the error surface, thus decreasing the sensitivity of the network to small fluctuations in the error surface. In many cases, the training rule stands a chance of escaping the local minimum even without momentum.

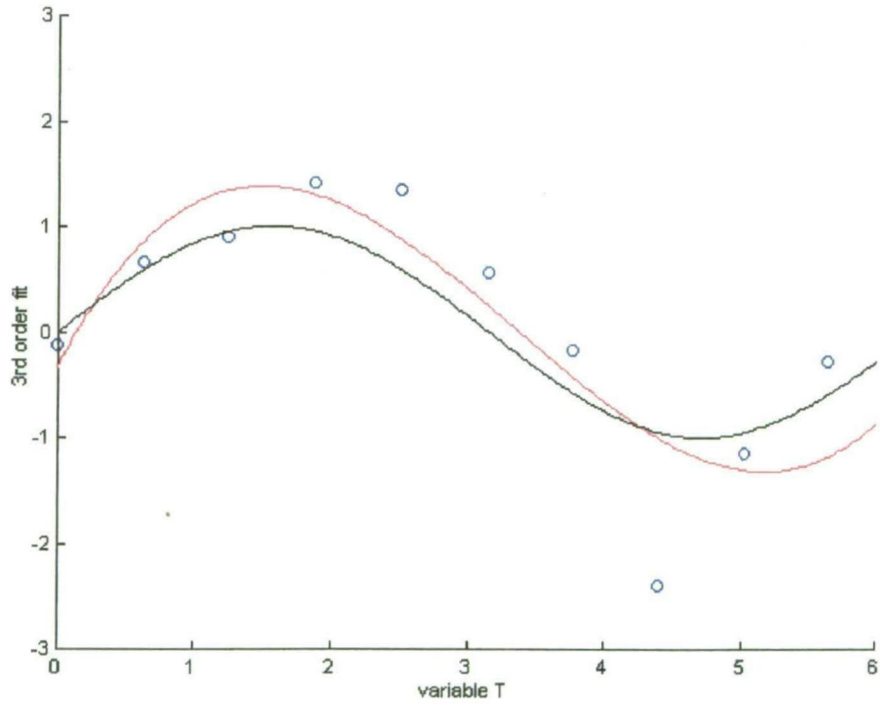
4.3.5 Network Specification

Demuth and Beale (1998) and Bishop (1995) note that backpropagation networks with a relatively large number of neurons compared to the complexity of the data, can exhibit behaviour analogous to classical polynomial overfitting. This is important, since a trained network is applied to data other than that used to train it.

The classical case of overfitting a polynomial curve to data is shown in Figure 4.4, which illustrates an exercise discussed by Bishop (1995). Data are produced by sampling a sinusoidal function, and using a random number to generate noise. Cubic and 9th order polynomials are then fitted to the noisy data.



Ninth order polynomial fit to data



Cubic polynomial fit to same data.

Figure 4.4 3rd and 9th order polynomial fits (red lines) to noisy data (blue circles) based on a sine function (black line).

The high order polynomial tracks the sample data more closely than the cubic polynomial, but the cubic polynomial better models the systematic aspect of the data (the sinusoidal function). The low order polynomial thus generalises better to new data, while the higher order polynomial is said to overfit the data.

A good network can generalise well to new data and, although overfitting of neural networks is not well understood, one rule of thumb for designing a good network is not to specify too many neurons. Another rule of thumb is that a multi-layer backpropagation network often handles complex or noisy data better than a simpler network. In the case of linear networks, however, Demuth and Beale (1998) note that multiple layers are no more powerful than single layer networks.

4.4 Case Study: The Launceston Air Quality Index

4.4.1 Background

Launceston is located in north central Tasmania, in the Tamar Valley about 50 km south of Bass Strait. The city occasionally experiences poor air quality during the winter months, primarily due to wood smoke emissions from domestic wood heaters, and emissions from the Bell Bay heavy industrial area at the head of the estuary have also caused concern.

The regional air pollution has been studied by several workers (*e.g.* Low and Todd, 1984), the most comprehensive investigation to date being the Tamar Valley Airshed Study (Carter et al., 1995). This 3 year project for the State Government was managed by the author, then the principal environmental engineer of a Hobart consulting engineering firm, in association with the University of Tasmania, the CSIRO Division of Atmospheric Research, and the Monash University Centre for Applied Mathematical Modelling. The project developed a puff dispersion model, driven by a diagnostic wind model, and model input was based on data from 15 weather stations and from campaigns to gather upper air data (see Figure 4.5).

Two important air flows influencing the air quality of the Launceston area are the inland-bound sea breeze, which typically reaches the city in the late afternoon, and the sea-bound katabatic winds, which start in the late evening and grow in strength as radiative cooling produces cold air drainage flows from the high ground bounding the valley.

Figure 4.5 The author carrying out air quality measurements north of Launceston.

These air flows can recirculate pollutants, a problem exacerbated by air channelling by the local topography, and by the frequent inversions which characterise the area (Carter et al., 1995; Power 1999).

The air quality of the Launceston area has been monitored by several campaigns since the early 1990s, including the Launceston Air Pollution Study (Lyons, 1996), in which PM_{10} particulate sampling was carried out at four sites, and total suspended particulate sampling was carried out at a fifth site. Carnovale (1997) summarises the results of these studies, and concludes that ambient concentrations of PM_{10} particulates occasionally exceed the standards set by the U.S. Environment Protection Agency (they also exceed the standards set by the new Australian National Environment Protection Measure on Ambient Air Quality).

4.4.2 Classical Forecast Model

One response to the concerns about poor air quality in Launceston has been the development of an air quality index forecast model, by the Bureau of Meteorology (Shepherd, 1997). The model uses observed and forecast meteorological parameters to predict ground level concentrations of airborne PM_{10} particulates.

Shepherd (1997) used stepwise multiple linear regression to assess the usefulness of about 45 candidate meteorological variables as predictors of PM_{10} particulate concentrations. The PM_{10} particulate concentrations measured at the Ti Tree Bend air quality monitoring station were taken to be representative of air quality conditions in Launceston, based on advice from the Department of Environment & Land Management. The target variable was the

square root of the PM_{10} concentrations, since this transformation resulted in a near normal distribution (as noted, this produces a better regression analysis).

Several candidate forecast models were developed, the two most promising of which each used only five predictor variables, and had similar goodness-of-fit parameters when applied to base data sets. The preferred model relied more on observations, and less on forecast variables. Table 4.1 summarises the characteristics of this model with regard to its base data set of 114 records, and Table 4.2 shows the first five records.

Variable		**Coefficient**	**Model performance (baseline data)**	
A.	3 pm surface air temp (°C)	-0.3116	Residual standard error	1.1816
B.	3 pm cloud cover (oktas)	-0.2658	Multiple R-squared	0.4775
C.	3 pm surface wind speed (m/s)	-0.1316	F-statistic	19.74
D.	850 hPa wind speed (m/s)	-0.1613	Degrees of freedom	5 & 108
E.	Month	-0.4641	P (= 1-p) value	6.295×10^{-14}
	Intercept	16.9013		

Table 4.1 The air quality index regression model (Shepherd 1997).

3 pm surface air temp (°C)	3 pm cloud cover (oktas)	3 pm surface wind speed (m/s)	850 hPa wind speed (m/s)	Month	Sqrt(PM10) at Ti Tree Bend
-2	6	5.7	9	7	13.19
-5	1	5.1	9	7	7.21
2	1	3.6	13	7	9.64
6	7	10.3	14	7	2.65
3	7	2.1	14	8	7.55

Table 4.2 The first five records of the base data set used to develop the Shepherd (1997) regression model (courtesy of the Bureau of Meteorology).

From the discussion earlier in this chapter, the F-statistic in Table 4.2 is computed as:

$$F = \frac{R^2/k}{\left(1-R^2\right)/(n-k-1)}$$

$$= \frac{0.4775^2/5}{\left(1-0.4775^2\right)(114-5-1)} = 19.74$$

For 5 and 108 degrees of freedom, the top 1% of the F-distribution values are those values for which $F > F_0$, with $F_0 = 9.13$ obtained from tables in Hoel (1947). Clearly, the value F = 19.74 lies in this region, and the linearity assumption is a therefore expected to be a good one. This is a little surprising from a physical viewpoint, since the predictor variables are

proxies for more conventional measures of atmospheric stability, such as the environmental lapse rate, or sigma-theta (the standard deviation of the horizontal wind direction).

All the 3 pm values listed in Table 4.1 are measured at Launceston airport on the day prior to the forecast, while the upper air wind speed is the forecast for this variable at 9 pm on the day of interest. Air pollution meteorology can rationalise the use of each predictor variable, since warm, windy and cloudy conditions in the summer months are all associated with good air quality, while cold, calm and clear sky conditions in the winter months are associated with episodes of high air pollution (Shepherd, 1997).

The model equation is thus:

$$\sqrt{PM_{10}} = -0.3116A - 0.2658B - 0.1316C - 0.1613D - 0.4641E + 16.9013$$

where the predictor variables A to E are defined in Table 4.1. The predicted PM_{10} particulate concentrations are converted to an air quality index, and reported as part of weather forecasts. Typically, the concentration ranges 0-40 $\mu g/m^3$, 41-80 $\mu g/m^3$, 81-120 $\mu g/m^3$and over 121 $\mu g/m^3$ correspond to Good, Poor, Bad and Very Bad air quality forecasts.

4.4.3 Neural Network Model

A two-layer backpropagation network was developed, using *MATLAB* software (Demuth and Beale, 1998), to provide an alternative air quality forecast model. The network comprised an input layer of 30 neurons with tangent-sigmoidal transfer functions, and an output layer of a single neuron with a linear transfer function.

The network was trained on the same 114 data records used by Shepherd (1997) to develop the regression model. The backpropagation algorithm *trainbpx* was used, employing both momentum and an adaptive learning rate (Demuth and Beale, 1998). Figure 4.6 shows the progress in training the network for the first 150 training epochs after initialisation of the network weights, and Figure 4.7 shows the performance of the trained network in predicting the response variables for the training data set.

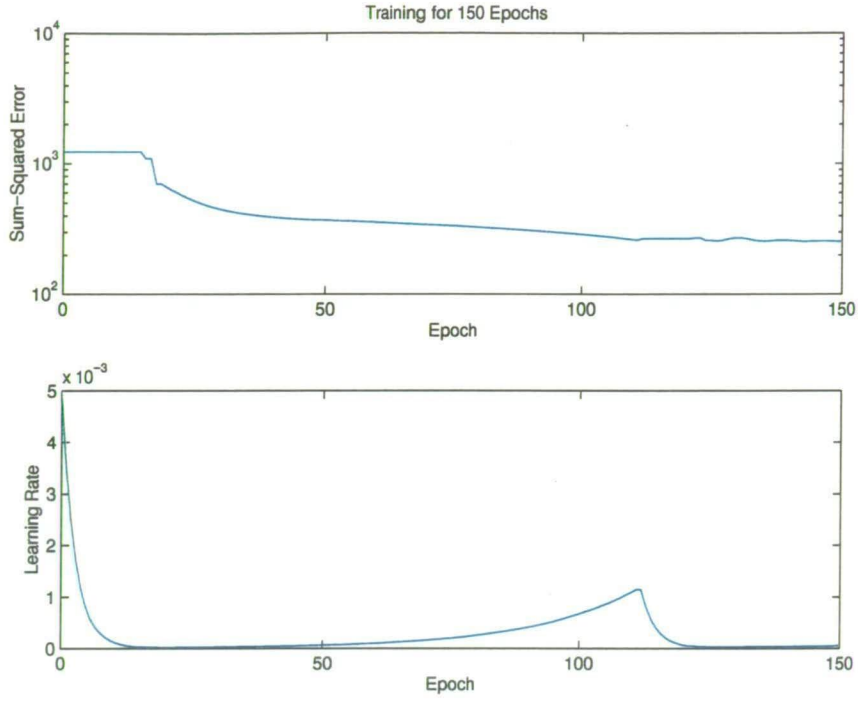


Figure 4.6 The network's training progress over the first 150 training epochs, showing error reduction and learning rate variation.

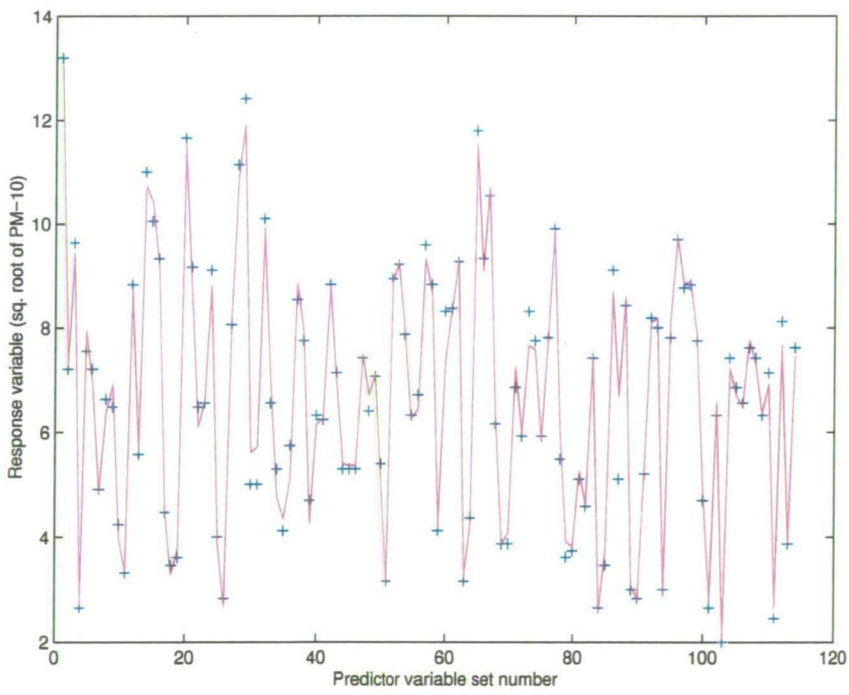


Figure 4.7 The network's performance in predicting the response variables in the original 114 training data records (five predictor variables per record).

4.4.4 Model Performance Comparison

Figure 4.8 compares the performances of the regression model and the neural network model in predicting PM_{10} particulate concentrations, when presented with a check data set. The regression model predictions have an R-square value of 0.64 (*i.e.* a correlation coefficient of R = 0.80) and an RMS error of 22.7. This is a little better than expected, given that the model's R-square value for the base data was 0.48 (R = 0.69). The neural network model predictions have an R-square value of 0.69 (R = 0.83), and an RMS error of 21.1, and thus the neural network slightly out-performs the regression model.

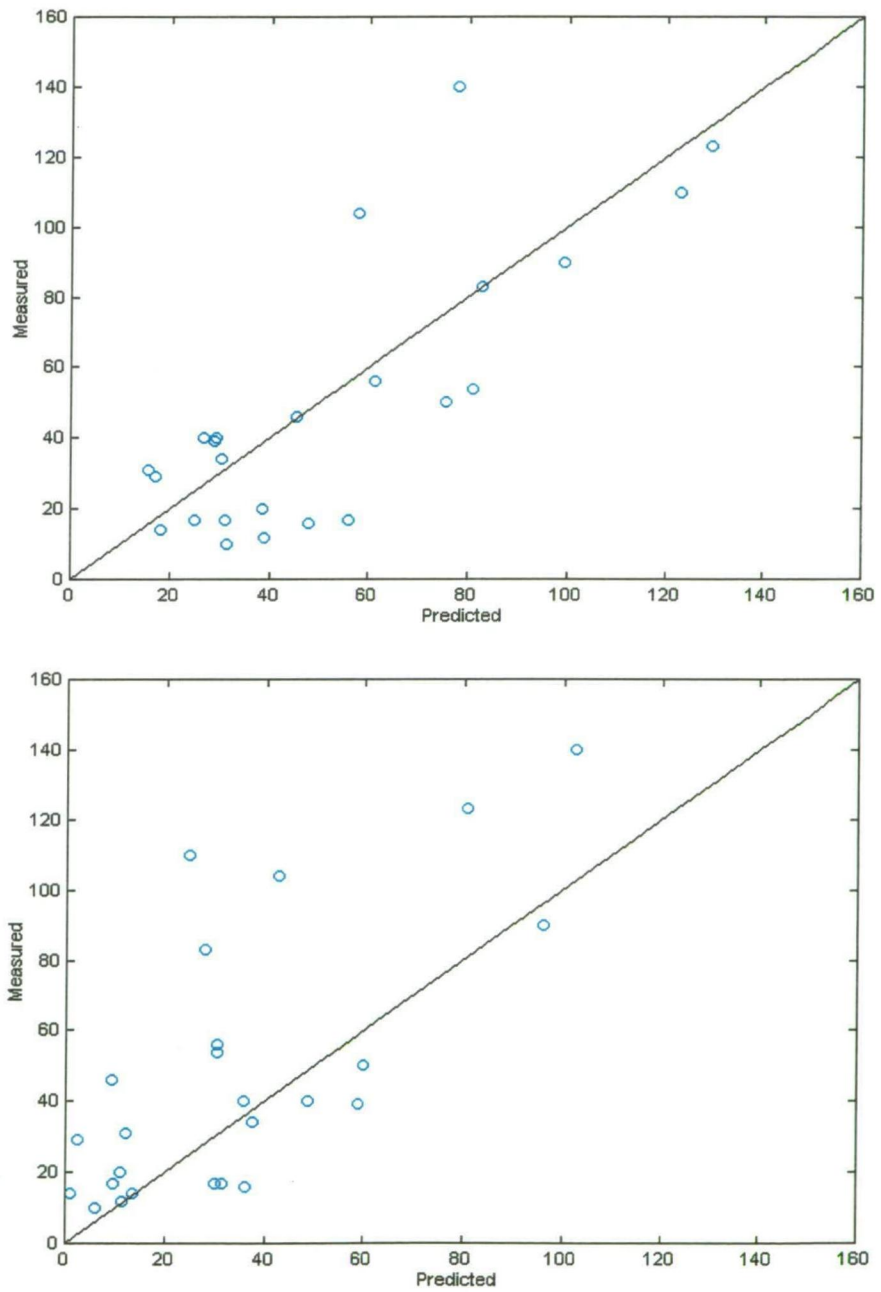


Figure 4.8 Scatter diagrams of predictions vs. check data measurements for the regression model (top) and the neural network model (bottom).

4.5 Case Study: Sewage Treatment Plant

4.5.1 Treatment Process Description

The Ti-Tree Bend sewage treatment plant serves the City of Launceston in north-central Tasmania, and treats sewage from four major pump stations. Primary treatment equipment was commissioned in 1978, the plant was upgraded to provide full secondary treatment in 1989, and disinfection operations commenced in late 1992.

Preliminary sewage treatment involves coarse screening by mechanically raked bar screens, and grit removal in aerated chambers. From the inlet works, the sewage flows through two standing wave flumes to screw pumps, which lift the liquid into the aerated inlet channel to four primary sedimentation basins. Settled solids, grease and scum are removed from the basins by surface skimmers and bottom scrapers, and pumped to digesters.

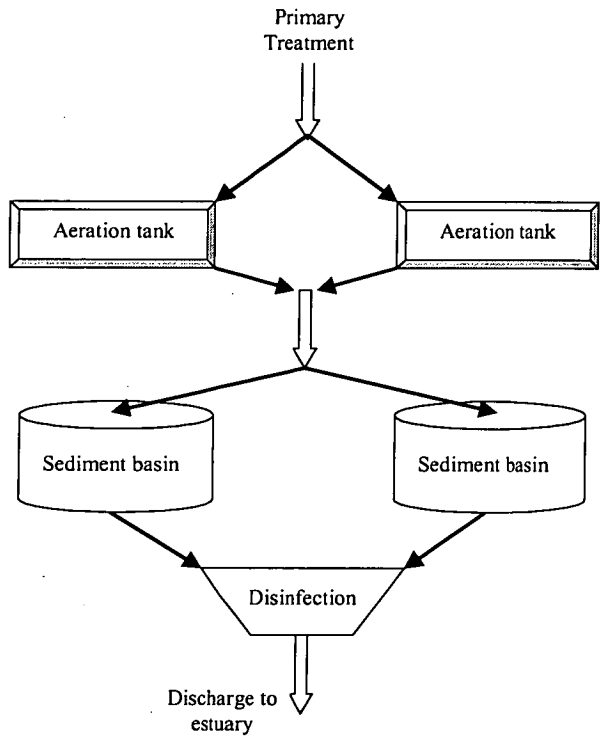


Figure 4.9 Secondary sewage treatment.

Effluent from the primary sedimentation basins undergoes secondary treatment in two aeration tanks, as shown in Figure 4.9. The process uses activated sludge, whereby the sewage is mixed with a biologically active sludge. The sludge feeds on the dissolved and colloidal organic matter, and hence multiplies. The mixture is stirred and oxygenated by surface aerators.

After a detention period of 10.37 hours in the aeration tanks (at mean dry weather flow), the liquor is combined and passed to two secondary sedimentation basins, where the activated sludge settles out and is returned to the aeration tanks. The treated effluent is directed to the chlorine contact tanks for disinfection to kill pathogenic organisms, and then discharged to the Tamar Estuary.

4.5.2 Quality Control Tests

Liquor from both aeration tanks is sampled daily and tested on-site for pH, alkalinity and suspended solids. The sludge levels within the aeration tanks are controlled to maintain suspended solids levels of just over 2,000 mg/L. The clarity of treated sewage in both secondary sedimentation basins is measured four times a day, with good clarity reflecting good performance of the secondary treatment process. A decrease in clarity indicates that the activated sludge process may require corrective action.

The discharge to the Tamar estuary is sampled regularly for compliance with the plant's licence conditions, which require the suspended solids (SS) content and biological oxygen demand (BOD) of the discharge to be no more than 60 mg/L and 40 mg/L respectively.

Table 4.3 shows several typical data records from 1997. The aeration tank data refer to measurements from only one of the two tanks, but there is rarely a significant difference between concurrent measurements from the two tanks. Similarly, the clarity data refer to measurements from only one of the two secondary sedimentation basins, but again there is rarely a significant difference between concurrent measurements from the two basins.

	Aeration tank measurements			**Sed. Tank**	**Discharge (mg/L)**	
Date	*SS (mg/L)*	*pH*	*Alk (mg/L)*	*Clarity (m)*	*BOD*	*SS*
14 Oct 97	2800	6.8	90	0.90	8	12
23 Oct 97	2200	6.9	82	0.65	6	11
30 Oct 97	2200	6.8	66	0.25	7	39
7 Nov 97	2200	6.4	46	0.28	12	39
12 Nov 97	1800	6.6	52	0.25	15	49

Table 4.3 Typical predictor variable and discharge quality data.

The sewage treatment plant operators would benefit from a model to predict the discharge quality parameters (SS and BOD) from the measurements taken in the aeration tanks. The suspended solids test takes about two hours, but an accurate BOD test takes five days, which can lead to over a week passing between detecting a problem and correcting it.

Aeration tank data and secondary sedimentation basin clarity data are available from 31 August 1994 to 30 June 1998, comprising 179 complete records. Additional data excluding clarity measurements are available from 14 April 1992, shortly after the disinfection process was commissioned.

Table 4.4 gives the correlations between the four predictor variables, namely the aeration tank and sedimentation basin measurements, and the two discharge quality parameters (BOD and the suspended solids). The correlations were assessed using all 179 available records.

	SS tank	*PH*	*Alkalinity*	*Clarity*
BOD	-0.290	-0.161	-0.147	-0.478
SS discharge	-0.179	-0.211	-0.180	-0.670

Table 4.4 Correlation coefficients (R values) between the four predictor variables and the two discharge parameters.

None of the four predictor variables correlates very well with either of the discharge quality parameters. Clarity is the strongest predictor variable and, not surprisingly, it correlates particularly well with the measurement of suspended solids at discharge. Two other predictor variables, the maximum temperature of the aeration tank liquor, and the flow rate, were dismissed from further consideration, since both measurements had correlation coefficients of less than 0.1 with respect to the two discharge quality parameters.

4.5.3 Regression Models

Two linear regression models were developed, using the S-Plus software (MathSoft, 1995), to predict the BOD and SS discharge parameters. The base data set consisted of the 73 records from 2 January 1997 to 30 June 1996. The remaining 106 records, from 31 August 1994 to 18 December 1996, were used as a check data set.

The model equations are as follows:

$$BOD\ (mg/L) = -0.0038A_1 - 7.6988B_1 + 0.0420C_1 - 8.1609D_1 + 70.0031$$

$$SS\ (mg/L) = -0.0020A_2 - 5.2541B_2 - 0.0556C_2 - 38.6400D_2 + 83.4784$$

The predictor variables A_1 to D_1 and A_2 to D_2 are given in Table 4.5, together with the model performance characteristics relating to the base data set. Both models are weak, with R-square values of only 0.3193 and 0.4179 respectively. The 5% and 1% values for the tail end of the F-distribution are 5.69 and 13.65 respectively, for 4 and 68 degrees of freedom. For both models, the F-statistic (computed to test the significance of the R-square value) lies within the top 5% of F-distribution values, but not within the top 1% of values.

BOD model			
Variable	**Coefficient**	**Model performance (base data)**	
A_1. SS in aeration tank (mg/L)	-0.0038	Residual standard error	4.883
B_1. pH in aeration tank	-7.6988	Multiple R-squared	0.3193
C_1. Alkalinity in aeration tank (mg/L)	+0.0420	F-statistic	7.976
D_1. Clarity in clarifier (m)	-8.1609	Degrees of freedom	4 & 68
Intercept	70.0031	P (= 1-p) value	0.000025
SS model			
A_2. SS in aeration tank (mg/L)	-0.0020	Residual standard error	13.47
B_2. pH in aeration tank	-5.2541	Multiple R-squared	0.4179
C_2. Alkalinity in aeration tank (mg/L)	-0.0556	F-statistic	12.2
D_2. Clarity in clarifier (m)	-38.6400	Degrees of freedom	4 & 68
Intercept	83.4784	P (= 1-p) value	1.56×10^{-7}

Table 4.5 The BOD and SS regression models.

One reason for the weakness of the regression models is that the linearity assumption is poor. Another reason is that several of the distributions of the four predictor variables and the two target variables depart significantly from the Gaussian distribution, which is a key assumption of the analysis.

Table 4.6 shows the performance of the two regression models when applied to the check data set. In both cases, the models perform significantly less well that the neural network models presented in the next section. (One must be careful of assessing model performance in the manner shown in Table 4.6: a model of BOD = 10 mg/L ± 10 mg/L accounts for some 95 % of the data points !).

	Base data		*Check data (106 records)*	
	BOD	*SS*	*BOD*	*SS*
Correlation coefficient, R	0.56	0.65	0.53	0.76
No. of accurate predictions				
Within 2 mg/L of measurement	--	--	45 (42%)	19 (18%)
Within 5 mg/L of measurement	--	--	83 (78%)	59 (56%)

Table 4.6 Performance of the two linear regression models applied to the check data set. BOD = biological oxygen demand, SS = suspended solids at discharge (mg/L).

4.5.4 Neural Network Model

Sewage treatment plant staff were unable to identify (expert) rules to describe the relationships between the aeration tank measurements and the discharge quality, although such rules might be established for the sediment basin (clarity) measurement. It was thus decided that a neural network approach to predicting the discharge quality should be used, in favour of a fuzzy rule system. This exercise can be viewed as aggregating the predictor variables (indicators) into two indices.

As for the regression models, the neural network training data set comprised the 73 records from 2 January 1997 to 30 June 1996; and the remaining 106 records, from 31 August 1994 to 18 December 1996, were used as a network performance check data set. As for the air quality index case study, tangent-sigmoidal transfer functions were specified for both the input and the hidden layer neurons, linear transfer functions were specified for the output neurons; and the backpropagation algorithm *trainbpx* was used to train the network, whereby an adaptive learning rate and momentum are used to aid the error descent training.

Several network architectures were examined. First, the performances of two layer networks were compared to the performances of three layer networks, and three-layer networks were found to slightly outperform two-layer networks with a comparable numbers of neurons. A three-layer network to predict just one discharge parameter performed satisfactorily when a minimum of 20-30 neurons was specified in both the input layer and the hidden layer.

Second, the performance of separate three-layer networks to predict the discharge BOD and SS values was compared to the performance of a single three-layer network to predict both parameters. Overall, the use of two separate networks was found produce slightly better performance than a single network, but the performance differences were minimal, and did not outweigh the advantage of simplicity associated with using a single network.

A three-layer network which predicted both discharge parameters needed a minimum of about 30 neurons in both its input layer and its hidden layer (and two neurons in the output layer), in order to perform satisfactorily. Figure 4.10 shows this network, and Figure 4.11 shows its performance, when trained to a sum-squared error of 9,270, when the reduction in SSE per training epoch had slowed significantly. Figure 4.12 shows the network's performance in predicting the discharge parameters for the check data set, and Table 4.7 summarises the performance descriptors.

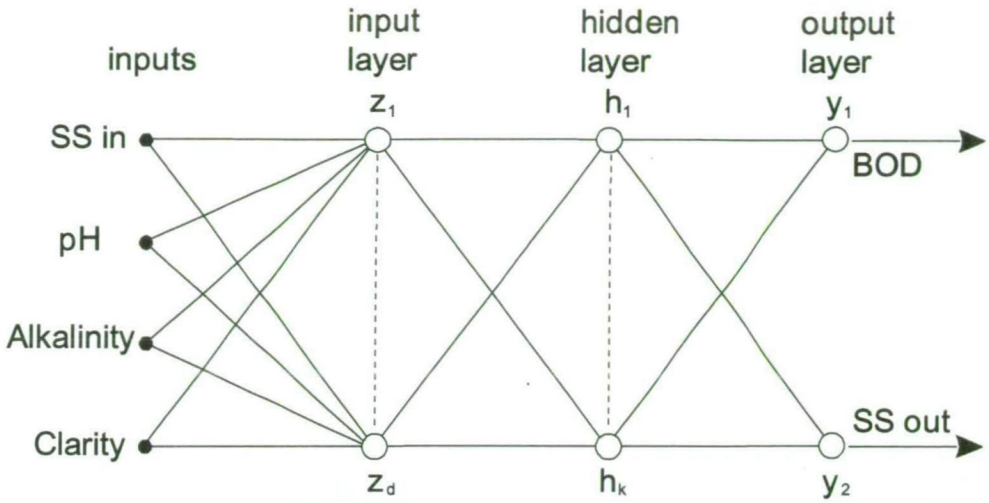


Figure 4.10 Three-layer network used to predicted both BOD and SS. The input and hidden layers each have 30 neurons. The output layer has two neurons.

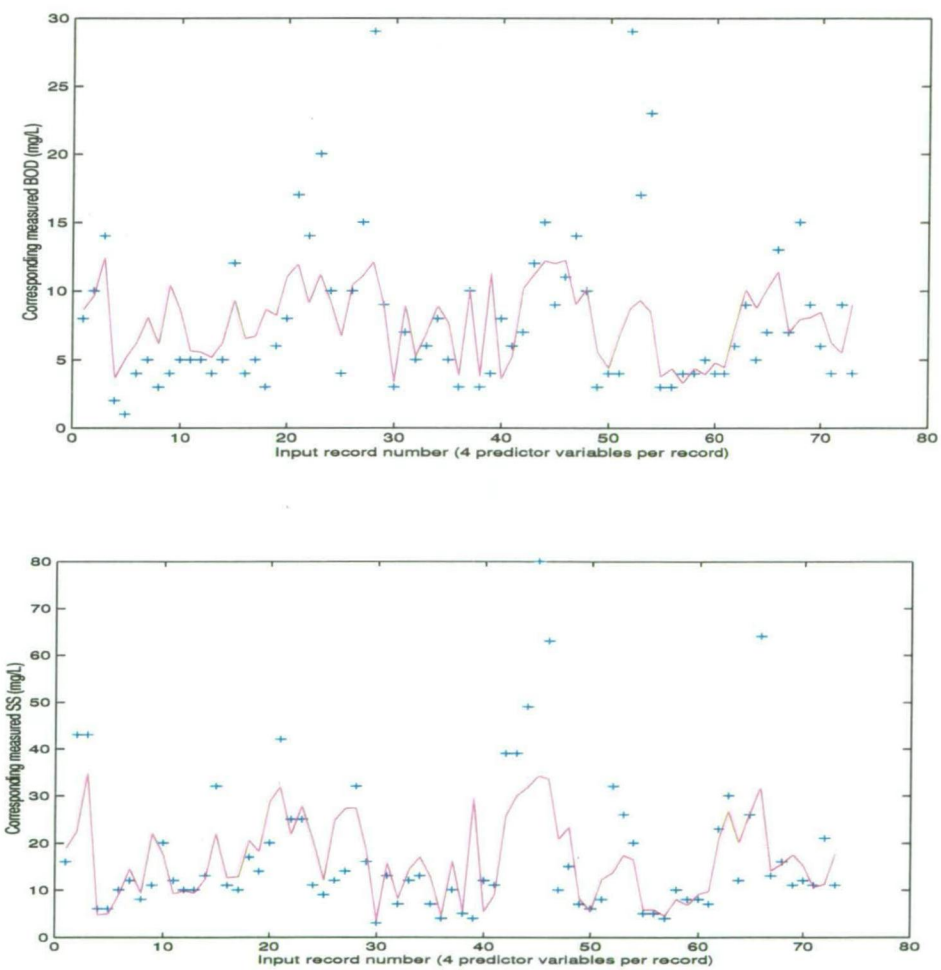


Figure 4.11 Performance of the 3-layer network in predicting the training data target records of BOD (mg/L); and SS (mg/L). The network's sum-squared error is 9,270.

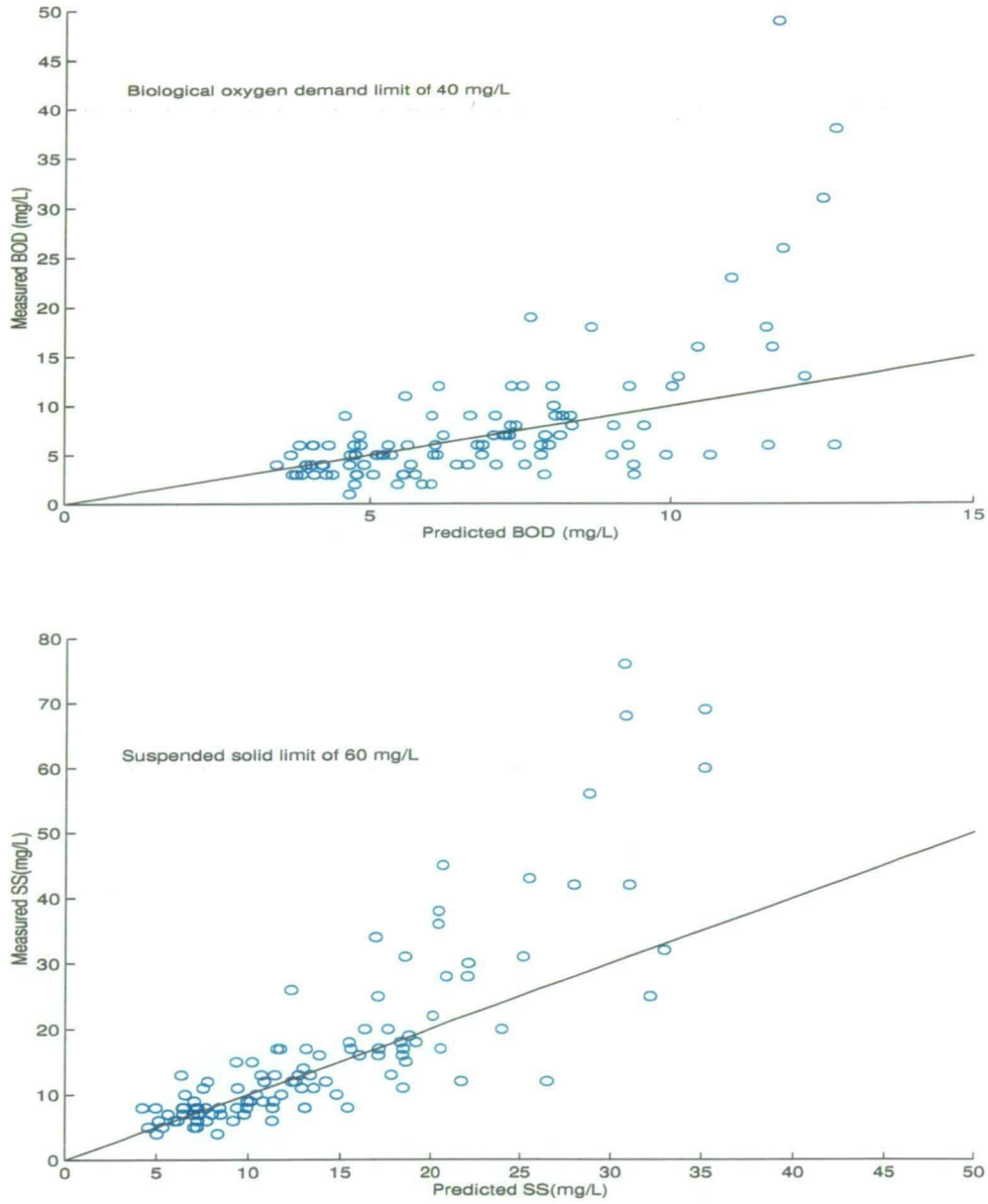


Figure 4.12 Scatter diagrams showing the performance of the network (SSE = 9,270) in predicting BOD and SS (both mg/L), for the check data.

	Base data		*Check data (106 records)*	
	BOD	***SS***	***BOD***	***SS***
Correlation coefficient	0.60	0.76	0.64	0.83
No. of accurate predictions				
Within 2 mg/L of measurement	--	--	61 (58%)	47 (44%)
Within 5 mg/L of measurement	--	--	90 (85%)	75 (71%)

Table 4.7 Performance statistics of the network (SSE = 9,270) applied to the check data set.

The performance of the network is quite good, except that it tends to underpredict high values of the target variables. An obvious question is whether it could perform better in predicting high index values if it were trained further. Figure 4.13 shows the performance of the same three-layer network in approximating the training data, when trained to a sum-squared error of 5,370 (when the change in SSE per training epoch was negligible), and Table 4.8 gives the performance descriptors for this network.

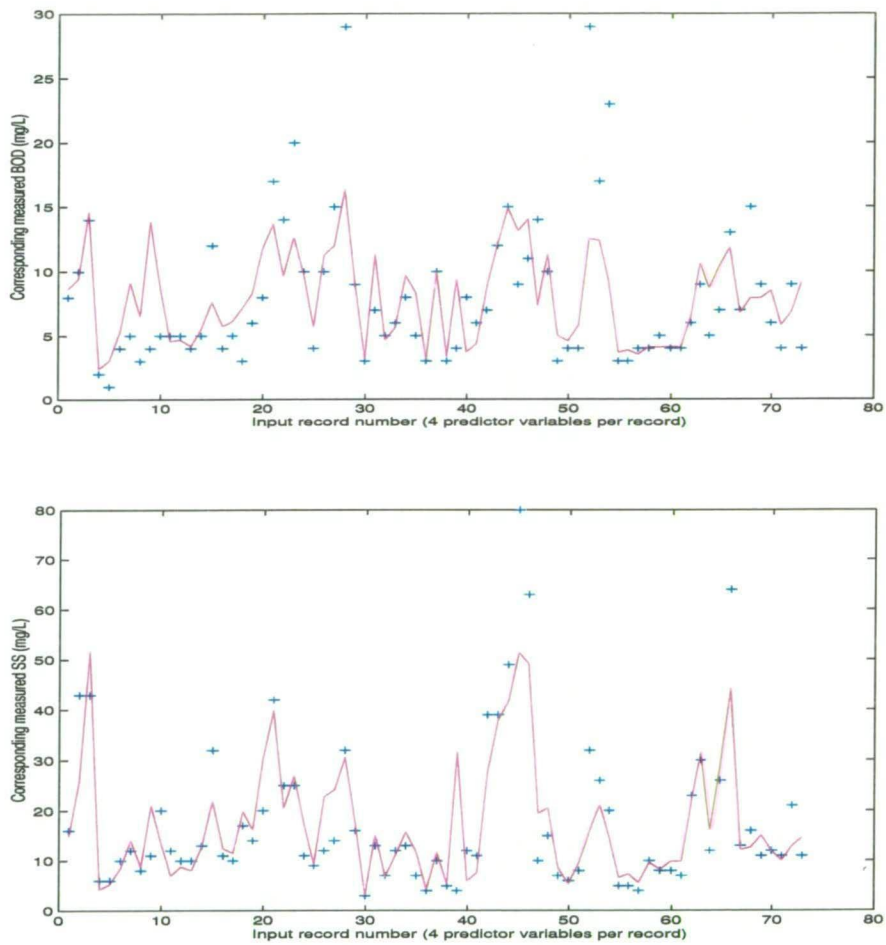


Figure 4.13 Performance of the same 3-layer network in approximating the training target variables when trained to a sum-squared error of 5,370.

	Base data		*Check data (106 records)*	
	BOD	***SS***	***BOD***	***SS***
Correlation coefficient	0.70	0.87	0.58	0.86
No. of accurate predictions				
Within 2 mg/L of measurement	--	--	53 (50%)	43 (41%)
Within 5 mg/L of measurement	--	--	88 (83%)	75 (71%)

Table 4.8 Performance statistics of the network (trained to SSE = 5,370) applied to the check data. BOD and SS both in mg/L.

Comparison of Tables 4.7 and 4.8 shows that the network's approximation of the base data has improved with further training, but its ability to generalise to new data has diminished in the case of BOD predictions, and has not significantly changed in the case of SS predictions. This behaviour is analogous to overfitting a classical polynomial, discussed earlier.

From a physical point of view, it is unlikely that it is possible to further improve the network performance. The predictor data are measurements from only one of the two aeration tanks, and from only one of the two secondary sedimentation basins. Furthermore, the predictor data are single measurements taken at 9:00 am, whereas the discharge parameters (BOD and SS) are measured from about eight composite samples of the discharge. Moreover, sewage treatment plant staff advise that measurements are accurate only to about ± 10 %.

Considering the network training performance diagram (Figure 4.12), it is clear that the network is good at predicting low values of BOD and SS, but that it tends to underpredict those occasions when in fact high values of BOD and SS were measured. The reason for this is that the training data contained very few high BOD and SS measurements (see Figure 4.12), since the sewage treatment plant usually operates well within its licence conditions. Therefore, the network was unfamiliar with upset situations.

It can be concluded that the network's predictions of low BOD and SS measurements are usually accurate, but that predictions of BOD values higher than about 10 mg/L, or of SS values higher than about 20 mg/L, should be taken as indicative of actual values which are higher than the predictions.

4.6 Review and Conclusions

This chapter has examined traditional (regression analysis) and neural network approaches to aggregating indicators into an index, methods that are appropriate for situations in which the relationships between the indicators and the index are not well known.

For cases in which the relationships between the indicators and the index are approximately linear, and the variables are normally distributed, a simple multiple linear regression model can be developed, and a neural network does not offer a significant advantage over the classical approach. This was found to be the situation for the air quality index case study.

However, in some situations, the relationships linking the predictor and the target variables are not linear, or else the variables are not normally distributed. In such cases, it may be possible to develop a non-linear regression model, but the form of the non-linear equation to fit the data must be determined by trial-and-error or empirically, and transformations must be found to produce approximately normal distributions of the variables (the square root of the target variable was used in the air quality index regression model).

A neural network model can offer a more natural alternative to pattern recognition problems than attempting to develop a non-linear regression model. The network developed for the sewage treatment plant case study performed well, and this approach offered the additional benefit that a single model could predict both target variables, while separate regression models were needed.

Neural network theory and applications go far beyond the simple networks discussed in this chapter. For example, Demuth and Beale (1998) discuss recurrent networks, which are two-layer backpropagation networks with a feedback path between the outputs and the inputs. This allows the network to recognize temporal patterns in addition to spatial patterns.

Consider the following possible application. Chapter 3 examined a case study to calculate a roadside vegetation quality index. The Department of Transport recently took video footage of the length of Tasmania's Highway 1, the main trunk of the national highway in the State. It is conceivable that a neural network could process this video, and be trained to recognise the various components of roadside vegetation (native vegetation, weeds such as gorse, roadside width, and so forth). The network could then be applied to stretches of roadside which have not been subject to botanical surveys, and hence avoid considerable expenditure and effort in this regard.

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5.0 SUSTAINABILITY ASSESSMENT METHOD

5.1 Method Overview

Figure 5.1 overviews the sustainability assessment method. In brief, a situation is defined by sustainability indicators appropriate to the project being assessed, and an expert system based on fuzzy rules is used to predict how the project will change these indicators.

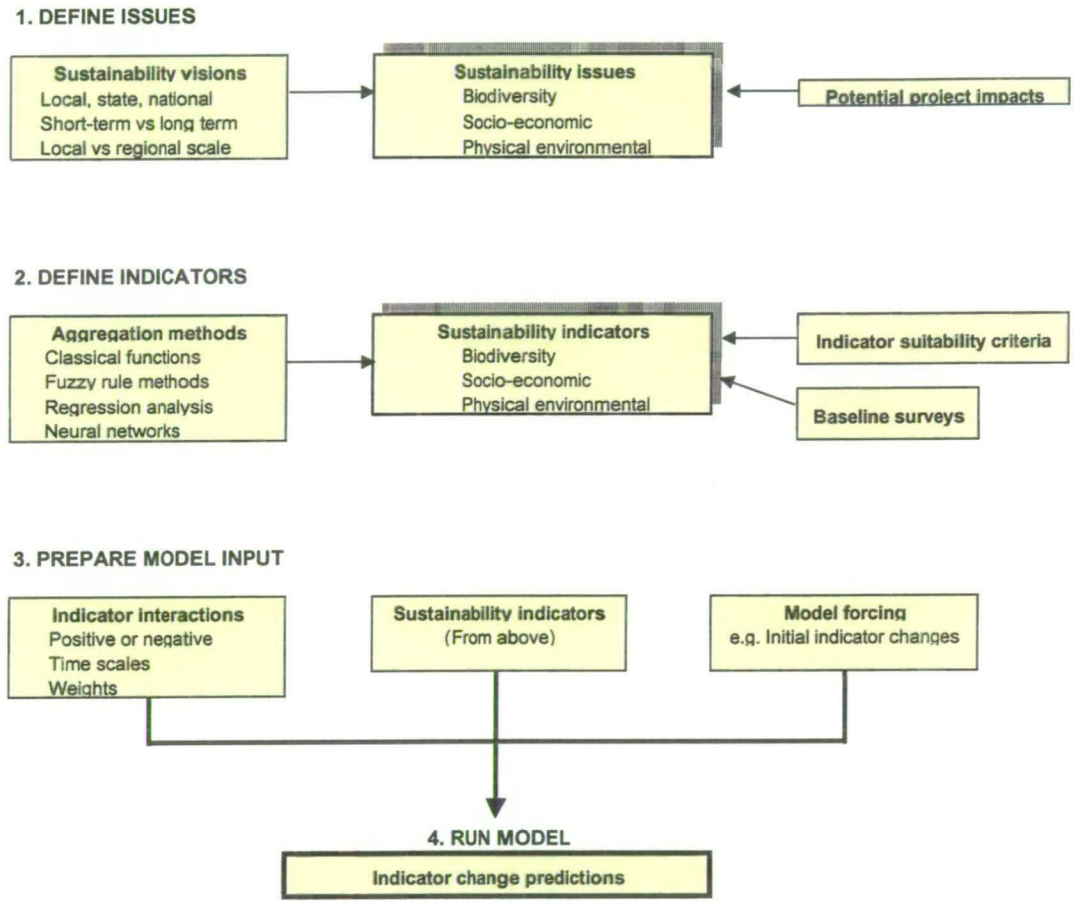


Figure 5.1 Overview of the sustainability assessment method.

Task 1. Define Issues

The first task in the assessment process is to define the sustainability issues which a project can influence, paying particular attention to issues identified by any applicable sustainability vision. As discussed in Chapter 2, it is convenient to organise issues into biodiversity, socio-economic, and physical environmental themes, since this is how many planners think about projects, and it matches the scope of specialist studies which support a proposed project.

Task 2. Define Indicators

The second task is to define a cohesive set of indicators to describe the sustainability issues. (It is here understood that "indicators" means indicators and/or indices). Using as small a set of indicators as possible helps to avoid indicator redundancy, and keeps the assessment simple. If an issue derives from an established sustainability vision, then the choice of indicator should already have been made. For the remaining issues, the aggregation methods discussed in Chapters 3 and 4 may help to reduce the number of required indicators.

Tasks 3 and 4. Prepare Model Input and Run Model

The final tasks are to prepare and use a computer model to predict changes to the indicators due to the project. The modelling approach and details are discussed below.

5.2 Modelling Approach

5.2.1 The system to be modelled

The system variables are the sustainability indicators, the baseline values of which are determined by surveys and studies. It is assumed that the initial state of the system is one of equilibrium, such that the baseline indicator values are steady.

The project drives changes to the indicators, which interact through a range of processes. The modelling task is to predict the final values of the indicators as the system settles down to a new equilibrium state. The sustainability impact of the project is then defined by the overall changes in the indicator values. This modelling task is similar to climate modelling, and in particular to the exercise of predicting temperature changes in response to an increase in greenhouse gas concentrations.

The basic interaction between two system components is that a change ΔA in component A leads to a change ΔB in another component B. A *positive* interaction is one for which the response ΔB has the same sign as ΔA. For example, an improvement in a region's physical environment quality may produce an improvement in its biodiversity. A *negative* interaction is one for which the response ΔB has the opposite sign as ΔA. For example, an improvement in a socio-economic indicator due to urban expansion may produce a degradation of the physical environment.

A *feedback* interaction between the two components occurs when the change ΔB causes a further change, $(\Delta A)'$, in component A. The required model must pay great attention to feedbacks, since most sustainability indicators interact in a two-way manner, even if the feedback is weak. A *positive* feedback is one for which the further change, $(\Delta A)'$, is of the same sign as ΔA, thus amplifying the original change. For example, degradation of soil quality will lead to poorer vegetation, which in turn leads to erosion problems, further degrading the soil quality. A *negative* feedback is one for which $(\Delta A)'$ is of the opposite sign as ΔA, thus reducing (damping) the original change. For example, improvement in estuary water quality allows fish farms to be established, resulting in growth of the local community. The community growth is associated with an increase in sewage discharge and stormwater run-off, which leads to degradation of the estuary water quality.

Consider a set of fingerprint indicators, $Ind = \{Bio, Soc, Env\}$, with baseline values Ind^{base}. The project produces an initial set of indicator changes, $\Delta Ind^{initial}$, which trigger further indicator changes due to various feedbacks, such that the final set of indicators is:

$$\begin{aligned}\Delta Ind &= Ind^{final} - Ind^{base} \\ &= (\Delta Ind)^{initial} + \sum (\Delta Ind)^{feedbacks} \\ &= g\,(\Delta Ind)^{initial}\end{aligned}$$

where g is the gain of the system with respect to the initial changes. The overall system is expected to be characterised by a negative feedback, or else it would be unstable, but this does not mean that changes due to feedbacks are necessarily small compared to the initial changes. In the case of climate models, the temperature change due to feedback effects can be larger than the initial temperature change associated with an increase in the concentration of greenhouse gases (pers. comm. Professor Bill Budd, Antarctic CRC, Hobart).

Interactions occur over characteristic time scales, which must be taken into account by any attempt to model a system of variables. Climate system interactions involving glaciers or the deep ocean occur over much longer periods than interactions involving water vapour or vegetation (IPCC, 1990; Henderson-Sellers and McGuffie, 1987).

5.2.2 Traditional modelling approaches

The traditional approach to modelling a system of variables which are coupled through various interactions is to identify the differential equations which govern the system, and parameterise the interactions in terms of measurable quantities. The governing equations are then evaluated (numerically integrated) at regular time steps until the system settles down to its new equilibrium condition, using time steps which are small enough that the various interactions can be properly modelled.

Simple models seek only to describe the main interactions which link the system variables. For example, energy balance climate models predict global average temperature changes, and a popular perturbation exercise is to subject the model climate to an initial temperature rise by doubling the concentration of atmospheric CO_2.

More complex models include more physics, and can examine local changes to the system variables. The most sophisticated climate models have fully three-dimensional spatial grids, and are similar to general circulation weather models. They must be "spun up" until the model climate settles down to accord with present experience, and the concentration of greenhouse gases is subsequently increased according to some emission scenario. Such models can predict regional changes in variables, although these predictions lack certainty.

This traditional approach is not appropriate for the task of assessing a project's sustainability impact. Our understanding of regional sustainability interactions is not good enough that governing equations can be defined for the areas (*e.g.* a municipality) which are usually of interest to an assessment exercise; and the sustainability indicators are often known only semi-quantitatively. Overcoming these barriers would require both a major modelling exercise and a comprehensive field program to gather input data. An expert system approach using fuzzy-rules offers a promising alternative way forward, and this approach is described below.

5.2.3 An expert system modelling approach

A fuzzy rule model was developed using MATLAB software (Jang and Gulley, 1997), and Figure 5.2 shows the model flow chart for the simple case in which the model is forced (driven) by an impulse, defined as a set of initial indicator changes. The model iteratively computes subsequent indicator changes due to the interactions which link the indicators.

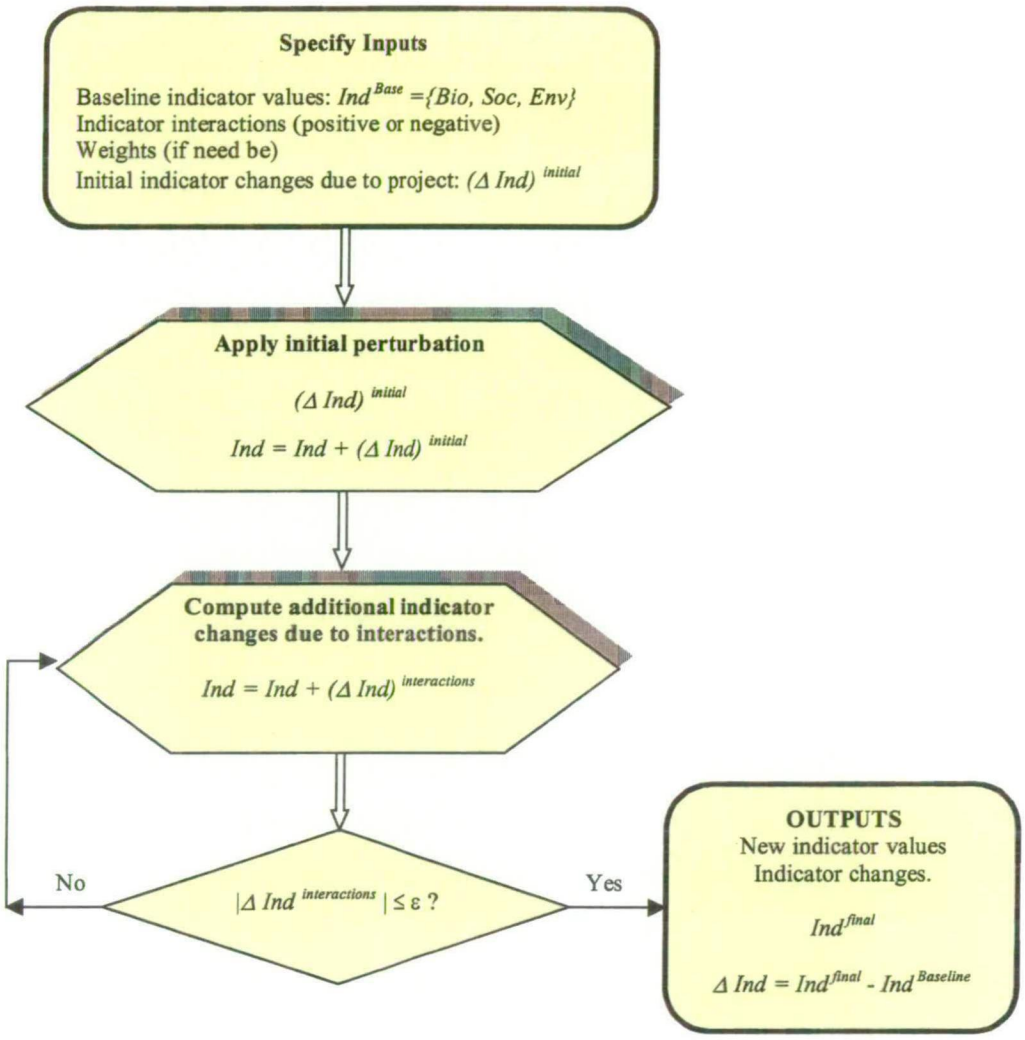


Figure 5.2 The model flow chart, for forcing by a set of initial indicator changes.

In brief, the model requires the following inputs.

1. Baseline indicator values.
2. Specification of the dominant indicator interactions.
3. The model forcing (*e.g.* initial changes to the baseline indicator values).
4. Specification of rule group weights, and of indicator change weights (if need be)

Prescribing the model forcing and the weights requires an understanding of the interaction response times, and this is discussed in detail below. For simplicity, it is assumed in this chapter that a single fingerprint indicator is adequate to describe each sustainability theme, and these indicators are denoted in the model flow chart as $Ind = \{Bio, Soc, Env\}$. In practice, it is often possible to use such extreme aggregation, especially when the assessment method is being used to compare project options.

The fuzzy rule system uses the minimum operator for inferences (the THEN operator), the maximum function for the AND operator, the OR operator is not used, and the model output is defuzzified by the centroid method. Other operators might be used, but there is no reason at present to diverge from this standard approach. Similarly, different membership functions might be used to represent model variables, but the fuzzy rule decision surfaces are not complex (see below), and experience suggests that the model predictions would not change significantly if trapezoidal or triangular membership functions were used in place of the Gaussian and sigmoidal functions.

5.3 Model Initialisation

5.3.1 Baseline indicators

The sustainability indicators are measured on the dimensionless scale of 0-10 introduced in Chapter 3. As shown in Figure 5.3, indicators can be mapped from their natural units on to this scale by interpreting their values in terms of the usual crisp (non-fuzzy) ranges {*Bad (0-2), Poor (2-4), Okay (4-6), Good (6-8), Excellent (8-10)*}.

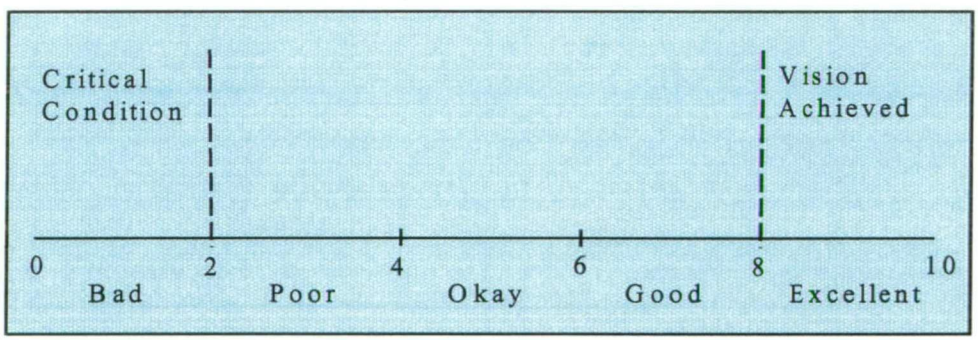


Figure 5.3 Interpretation of baseline indicator values on a scale of 0-10.

This approach is different to a traditional modelling approach, in which system variables are expressed in their natural units, and has been adopted for two reasons.

1. It facilitates the prescription of indicator values. For example, a study might find that a region's biodiversity indicator is "good", based on a variety of only semi-quantitative observations. The value of "good" is easily input to the model using the 0-10 scale.

2. It facilitates the interpretation of the indicators in planning terms. As shown in Figure 5.3, the *Bad* range denotes criticality of the indicator value, and the *Excellent* range denotes achievement of the sustainability vision, which is similar to the distance-to-target approach discussed by Harding & Eckstein (1996).

As an example of how to prescribe an indicator, consider the sound level impacting on an outdoor recreational area, measured as L_{eq}(day) in dBA, which is a logarithmic scale. Sound levels of $L_{eq}(\text{day}) \leq 55$ dBA are usually deemed acceptable for such areas, while sound levels of $L_{eq}(\text{day}) \geq 65$ dBA might trigger noise reduction measures. L_{eq}(day) sound levels of 65 dBA and 55 dBA would correspond to scale values of 2 and 8 respectively. L_{eq}(day) sound levels of about 75 dBA or more would all score close to zero, while L_{eq}(day) sound levels of about 45 dBA or less would all score close to 10.

5.3.2 Model forcing

The model can be forced in two main ways. The simplest forcing is when the project causes a set of indicator changes to occur over a short period of time, and the system then responds to this impulse. In the model flow chart, this impulse forcing is assumed to occur over an initial time step, and each subsequent iteration corresponds to an additional time step.

If a project has an ongoing impact, perhaps because of a continuing discharge of pollutants, then the model forcing should be applied over an appropriate number of times steps. The initial changes for the first time step are specified, and the model then computes additional changes due to indicator interactions, $\Delta Ind^{interactions}$, which occur over a second time step. The overall changes, ΔInd^{new}, are the sum of the changes due to the interactions, and the changes due to the ongoing forcing by the project over the second time step, $\Delta Ind^{forcing}$.

$$\Delta Ind^{new} = \Delta Ind^{interactions} + \Delta Ind^{forcing}$$

Ongoing forcing can be applied either by specifying changes to the indicators; or by including an additional variable in the model which describes the project's "activity". For example, in energy balance climate modelling, the additional variable would be radiative energy. Variables of interest (*e.g.* temperature, ice cover, water vapour) are parameterised in terms of the radiative energy, and a change in greenhouse gas concentrations drives the model by changing the radiative energy balance. In our model, the project "activity"

variable would be included alongside the indicators, and would drive changes to the indicators without being influenced in return. An example of this approach is given in Section 5.5, and also in the forestry case study presented in Chapter 6.

The model forcing depends on the nature of the project being assessed. In this chapter, an impulse forcing is specified directly in terms of initial indicator changes, but Chapter 8 shows how establishing the links between the model forcing and the project enables a preferred project option to be selected and optimised. For example, an initial change to an indicator describing air quality will depend on what air pollution control equipment is used.

5.3.3 Time Scales

It is important that the model accounts for the indicator interaction time scales. Fortunately, sustainability indicators are not associated with such vastly different interaction time scales as climate system components, since one criterion for screening candidate indicators is that indicators should have roughly similar characteristic time scales, and be able to respond to changes such that they provide early warning of problems (see Chapter 2). Nevertheless, acceptable indicators can still respond to system changes on time scales ranging from days to weeks, through to several years.

A system perturbed by a set of initial indicator changes will respond by moving to a new equilibrium, as the indicator interactions play themselves out. Its response time can be measured as the e-folding time in moving to its new equilibrium, which is the time taken to achieve $1/e^{th}$ (roughly one-third) of the indicator changes due to the indicator interactions.

The iterative approach to computing interactions means that each iteration can be interpreted as a time step, Δt, roughly equivalent to the time step used in a traditional model. In practice, the model is run until the indicator changes computed by an iteration are smaller than some tolerance. The iterative calculation process described below is such that 7 iterations after application of the last model forcing is generally sufficient to compute about 95 % of the additional indicator changes due to interactions, which corresponds to three e-folding times ($e^{-3} \approx 0.05$). In the case of impulse forcing, 7 iterations corresponds to 8 time steps, including the time step during which the initial indicator changes are applied.

This establishes a system response time which can be used to check that the size of the initial indicator changes is consistent with the assumption that they occur over a period that

is short compared to the time the system takes to respond to the changes. Knowing the system response time also allows the strengths of the indicator interactions to be specified in a consistent manner.

5.4 Calculation of Interactions

5.4.1 Approach

The inputs to the first iterative interaction computation comprise a) the initial indicator changes, $\Delta Ind^{initial}$; and b) the new indicator values, Ind^{new}, which are the baseline indicator values, Ind^{base}, updated by the initial indicator changes.

$$Ind^{new} = Ind^{base} + \Delta Ind^{initial}.$$

The model then uses a fuzzy rule system to calculate a set of indicator changes due to indicator interactions, $\Delta Ind^{interactions}$. These changes are augmented by any further changes due to ongoing forcing, $\Delta Ind^{forcing}$, as described earlier. The absolute indicator values are again updated and, together with the new set of indicator changes, are input to the next iteration.

In general, if the input and output indicator changes are denoted ΔInd^{old} and ΔInd^{new} respectively, then an iteration proceeds as follows:

$\{Ind^{new}, \Delta Ind^{old}\} \rightarrow$ apply fuzzy rules $\rightarrow \Delta Ind^{interactions}$

$\Delta Ind^{new} = \Delta Ind^{interactions} + \Delta Ind^{forcing}$

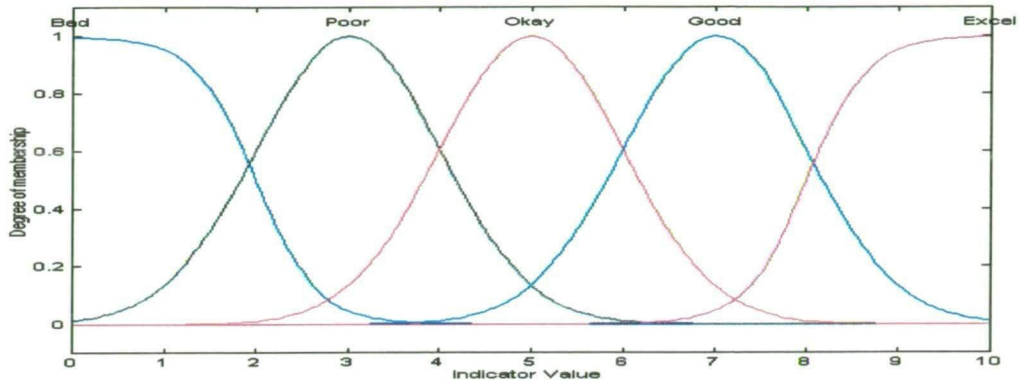
$Ind^{new} = Ind^{old} + \Delta Ind^{new}$

$\Delta Ind^{new} \longrightarrow \Delta Ind^{old}$

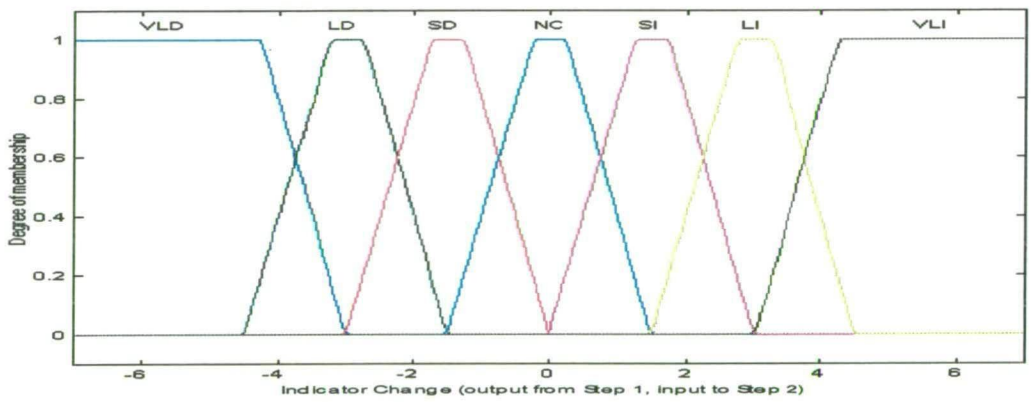
Repeat until $|\Delta Ind^{new}| <$ tolerance ε (see below)

5.4.2 Membership functions and fuzzy rules

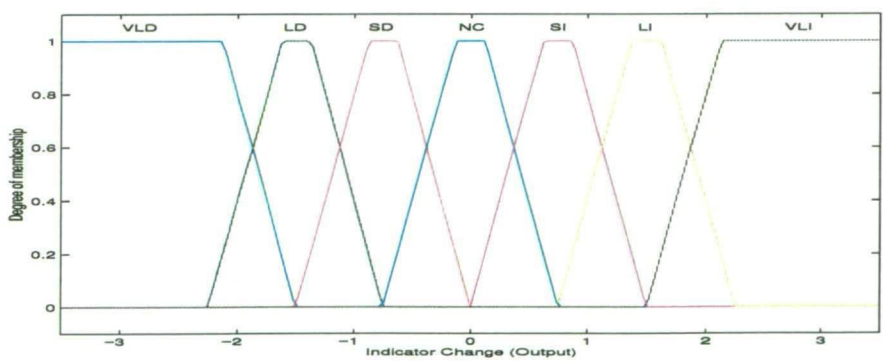
Figure 5.4 shows the membership functions used to fuzzify the variables used in the model, consisting of the absolute indicator values, the indicator changes computed by the previous iteration, and the new indicator changes computed by the iteration to hand.



Indicator membership functions. *Bad* and *Excel* are sigmoidal functions, while *Poor, Okay* and *Good* are Gaussian functions.



Input indicator change membership functions. All are trapezoidal functions.



Output indicator change membership functions, identical to the input indicator change membership functions (above), but with half the range. All are trapezoidal functions.

Figure 5.4 Membership functions for the indicator interaction calculations.

The output (new) indicator change membership functions are similar to the input (old) indicator change membership functions, but their ranges are smaller by a factor of half. Specifying a reduced range for the output indicator change membership functions converges the iteration. It also satisfies the common sense requirement that the overall feedback changes should be about the same magnitude, or less than, the initial indicator changes.

On completion of each iteration, $|\Delta Ind^{new}| < |\Delta Ind^{old}|$ is guaranteed, and the output (new) indicator change magnitudes are tested against a tolerance, ε. A choice of $\varepsilon \approx 0.1$ produces convergence close to the steady-state values within about 10 iterations, and the convergence process appears to be unconditionally stable.

As noted, seven iterations after the last application of model forcing is usually sufficient to compute some 95 % of the additional indicator changes due to indicator interactions. Five iterations might be expected to suffice, since $(0.5)^4 \approx 0.06$ and $(0.5)^5 \approx 0.03$, but the one-half ratio of the output indicator change range to the input indicator change range does not exactly correspond to a damping factor of one half.

Table 5.1 shows typical examples of sustainability interactions. If multiple interaction processes link two indicators, then it is assumed that the overall effect can be characterised as either a positive interaction or a negative interaction.

Inputs: Sustainability indicator values

		Biodiversity	**Socio-economic**	**Environmental**
Inputs Indicator Changes	ΔBio^{old}	Positive: revegetated area will expand once started.	Positive: improved wildlife improves tourist industry.	Positive: wetlands remove contaminants.
	ΔSoc^{old}	Negative: urban expansion destroys habitat.	Positive: inner city redevelopment improves business and residential potential.	Negative: expansion of human activities adversely impacts biodiversity.
	ΔEnv^{old}	Positive: degradation of water quality will adversely impact aquatic ecosystems.	Positive: better water quality improves recreational & resource potential.	Positive: acid gas emissions result in acidification of lakes.
		ΔBio^{new}	ΔSoc^{new}	ΔEnv^{new}

Outputs: Adjusted indicator changes, and hence new indicator values.

Table 5.1 Typical indicator interactions. The two negative interaction rule groups are unshaded. The positive interaction rule group is shaded.

Table 5.2 shows the rule groups in the first column of Table 5.1, which are used to calculate the new biodiversity indicator change, ΔBio^{new}. The two shaded rule groups denote positive interactions between the biodiversity indicator and itself, $\Delta Bio^{old} \rightarrow \Delta Bio^{new}$ (a positive self-feedback); and between the physical environmental and biodiversity indicators, $\Delta Env^{old} \rightarrow \Delta Bio^{new}$. The unshaded rule group denotes a negative interaction between the socio-economic and biodiversity indicators, $\Delta Soc^{old} \rightarrow \Delta Bio^{new}$.

The first three (upper left) rules in the three groups shown in Table 5.2 are, respectively:

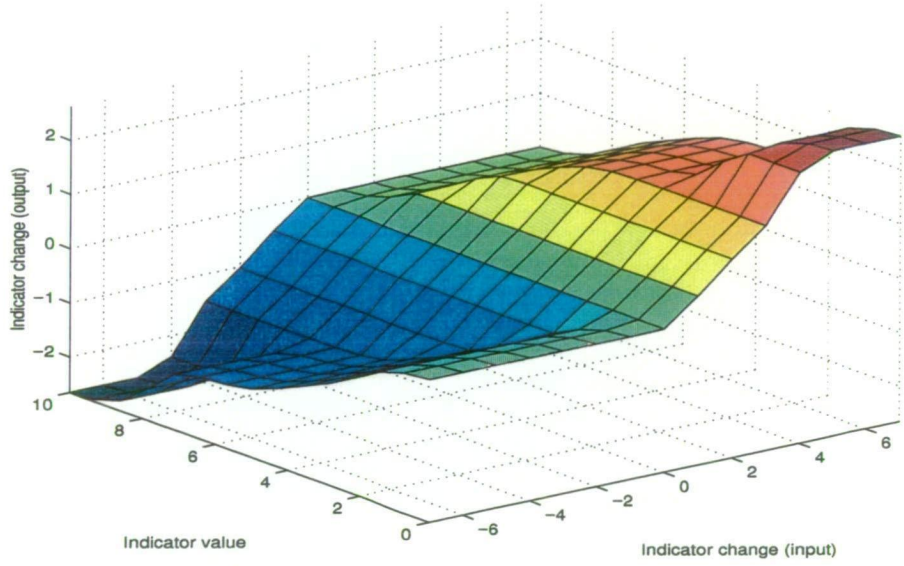
If (ΔBio^{old} is *VLI*) and (*Bio* is *Bad*) then (ΔBio^{new} is *VLI*)
If (ΔSoc^{old} is *VLI*) and (*Bio* is *Bad*) then (ΔBio^{new} is *NC*)
If (ΔEnv^{old} is *VLI*) and (*Bio* is *Bad*) then (ΔBio^{new} is *VLI*)

where *VLI* denotes Very Large Increase, and *NC* denotes No Change. As is usual for a fuzzy rule system, all 115 rules contribute to the calculation of ΔBio^{new}, but only a few rules significantly influence any given calculation: which rules these are depends on the inputs. The crisp (non-fuzzy) value of ΔBio^{new}, and the other crisp indicator change values, are obtained using the centroid method of defuzzification (see Chapter 3), and the absolute indicator values are then updated in preparation for the next iteration.

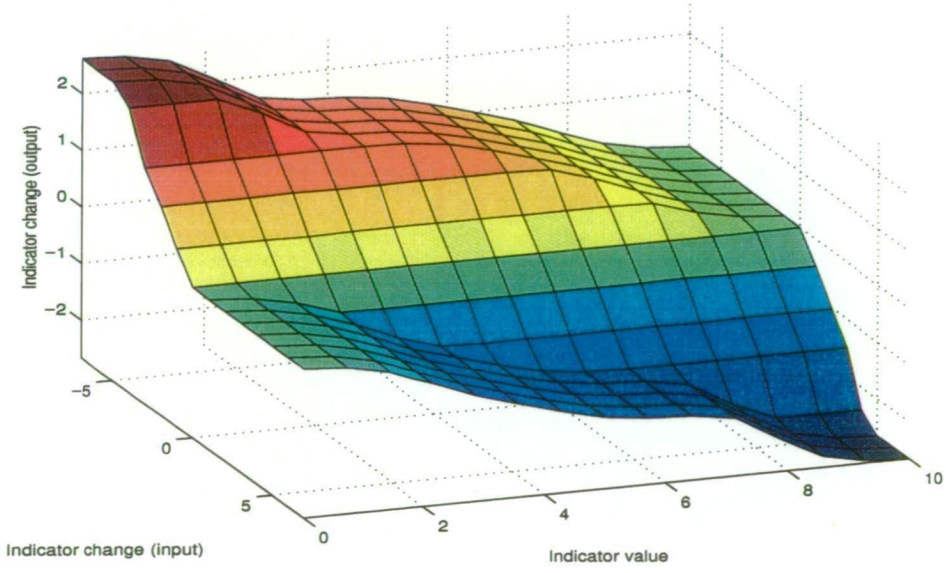
			Input: Biodiversity indicator				
			Bad	**Poor**	**Okay**	**Good**	**Excel**
Inputs Old indicator changes	**Old ΔBio**	**VLI**	VLI	LI	LI	SI	NC
		LI	LI	LI	LI	SI	NC
		SI	SI	SI	SI	SI	NC
		NC	NC	NC	NC	NC	NC
		SD	NC	SD	SD	SD	SD
		LD	NC	SD	LD	LD	LD
		VLD	NC	SD	LD	LD	VLD
	Old ΔSoc	**VLI**	NC	SD	LD	LD	VLD
		LI	NC	SD	LD	LD	LD
		SI	NC	SD	SD	SD	SD
		NC	NC	NC	NC	NC	NC
		SD	SI	SI	SI	SI	NC
		LD	LI	LI	LI	SI	NC
		VLD	VLI	LI	LI	SI	NC
	Old ΔEnv	**VLI**	VLI	LI	LI	SI	NC
		LI	LI	LI	LI	SI	NC
		SI	SI	SI	SI	SI	NC
		NC	NC	NC	NC	NC	NC
		SD	NC	SD	SD	SD	SD
		LD	NC	SD	LD	LD	LD
		VLD	NC	SD	LD	LD	VLD
			Output: New ΔBio				

Table 5.2 Fuzzy rules for a new biodiversity indicator change (compare to Table 5.1).

Figure 5.5 shows the output (decision) surfaces for the positive and negative rule groups. The input indicator change, ΔA, causes an indicator change ΔB which is of the same sign as ΔA in the case of a positive interaction; and which is of the opposite sign as ΔA in the case of a negative interaction. The absolute value of indicator B must be taken into account so that the updated absolute indicator value, B=B+ΔB, does not exceed the scale limits (0 and 10). In other words, the fuzzy rules depend in part on the absolute indicator values because a *Bad* indicator value cannot become much worse, and an *Excellent* indicator value cannot become much better.



Output surface for a positive interaction.



Output surface for a negative interaction.

Figure 5.5 Output surfaces for positive and negative interaction rule groups.

5.4.3 Weights and constraints

A project and its associated sustainability issues must be well enough understood that the interaction processes can be identified, but the individual fuzzy rules are predetermined by the choice of positive or negative rule group. It is only necessary to specify which rule group applies to each box of the interaction matrix since, in this simple model, the same positive or negative interaction rules are assumed to apply to all interactions.

This is a convenient aspect of the model, but the pre-determination of interaction fuzzy rules introduces the need to weight both the rules within each fuzzy rule group, and the set of indicator changes calculated by each iteration. It is also an implicit assumption about the nature of indicator interactions. For example, if a healthy ecosystem can better withstand pollution than a weakened ecosystem, then the fuzzy rules for the $\Delta Env^{old} \rightarrow \Delta Bio^{new}$ interaction should associate the largest negative values of ΔBio^{new} with absolute biodiversity indicator values in the *Okay* range, not the *Excellent* range.

It must be recalled that if the nature and size of ΔB were known for every interaction, then we would be able to identify the governing equations, and would use a traditional modelling approach to evaluate the indicator changes due to the interactions.

The rule group and indicator change weights are shown in Table 5.3 and, as is usual for weights:

$$\sum_i W_{ai} = 1 \quad \sum_i W_{bi} = 1 \quad \sum_i W_{ci} = 1 \quad \sum_i W_{di} = 1.$$

	Biodiversity	Socio-economic	Environmental
ΔBio^{old}	W_{a1}	W_{b1}	W_{c1}
ΔSoc^{old}	W_{a2}	W_{b2}	W_{c2}
ΔEnv^{old}	W_{a3}	W_{b3}	W_{c3}
	ΔBio^{new}, W_{d1}	ΔSoc^{new}, W_{d2}	ΔEnv^{new}, W_{d3}

Table 5.3 Weights for a typical interaction matrix.

Consider first the weights W_{ai}, W_{bi}., *and* W_{ci}. The W_{ai} weights define the relative importance of each of the three rule groups which contribute to calculation of the new biodiversity indicator change. For example, if the $\Delta Env^{old} \rightarrow \Delta Bio^{new}$ interaction is twice as strong as either the $\Delta Soc^{old} \rightarrow \Delta Bio^{new}$ interaction, or the $\Delta Bio^{old} \rightarrow \Delta Bio^{new}$ interaction, then the rules in the three groups would be weighted in the ratio:

$$\{W_{al} : W_{al} : W_{al}\} = \{2 : 1 : 1\} = \{0.5 : 0.25 : 0.25\}.$$

Similarly, the weights W_{bi} and W_{ci} apply respectively to the rule groups that contribute to calculation of the new socio-economic and physical environmental indicator changes.

The weights W_{di} apply to the set of new indicator changes, $\{\Delta Bio^{new}, \Delta Soc^{new}, \Delta Env^{new}\}$. These weights are needed because the characteristic size of the new indicator changes is determined by the membership functions which represent them, not by which rule groups are most important in contributing to the calculation. It may be necessary to adjust the relative sizes of the new indicator changes, and this is done through the weights W_{di}.

The indicator changes may also be subject to additional constraints, as required by the situation. For example, the final value of an indicator may be pre-determined, or the values of two indicators may be related. Examples of such constraints are given in the next section.

5.5 Modelling Basic Interactions

The modelling approach described above is intuitively reasonable, but it must be verified. Unfortunately, comprehensive regional sustainability check data are not yet available, but this section examines the modelling of simple indicator interactions; Section 5.6 presents an illustrative model application to a fictitious project; and the case studies in Chapters 6 and 7 provide further confidence in the assessment method and modelling approach.

5.5.1 Self-feedbacks

Basic rule group behaviour

Table 5.4 shows the basic indicator interaction box, with the rule group specified as positive or negative, as required.

	Indicator (absolute value)
ΔInd ^{old}	Positive or negative rules Time scale Weight = 1
	ΔInd ^{new} Weight = 1

Table 5.4 The basic self-feedback interaction.

Figure 5.6 shows the indicator change profiles which result from repeated application of the positive and negative rule groups, with a baseline indicator value of 2.0 and an initial change of 4.0. For the negative interaction rules, the final indicator value is 5.01 ± 0.05 after 6 applications. For the positive interaction rules, the final indicator value is 8.88, and 95 % of the 2.88 rise above the initial change is achieved after 13 applications.

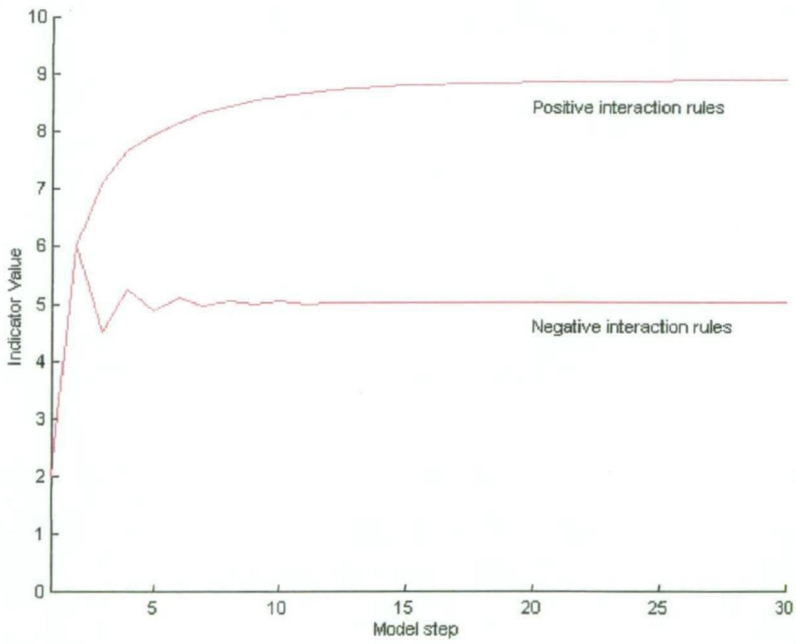


Figure 5.6 Repetitive application of positive and negative interaction rule groups.

For a given value of ΔInd^{old}, the interaction rules give larger new changes, ΔInd^{new} for mid-range absolute indicator values, and smaller new changes for high or low absolute indicator values. This ensures that the absolute indicator value remains bounded between 0 and 10. As noted, this feature of the model is different from a traditional model, which measures its variables in their natural units. Considering this difference, it can be appreciated that an already *Excellent* indicator value cannot get much better, and an already *Bad* indicator value

cannot get much worse. However, the interpretation of *Excellent* and *Bad* depends on the indicator. In the case of a water quality indicator, for example, indicator values less than 2 (the *Bad* range) on the 0-10 scale might correspond to contaminant concentrations greater than, say, 100 mg/L. Any contaminant concentrations significantly higher than 100 mg/L are treated similarly by the model. This aspect of the model's behaviour is acceptable, provided that one is aware that indicator interpretations are generally problem-specific.

Common self-feedbacks

Self-feedbacks drive growth or decay profiles, and two common profiles are shown in Figure 5.7.

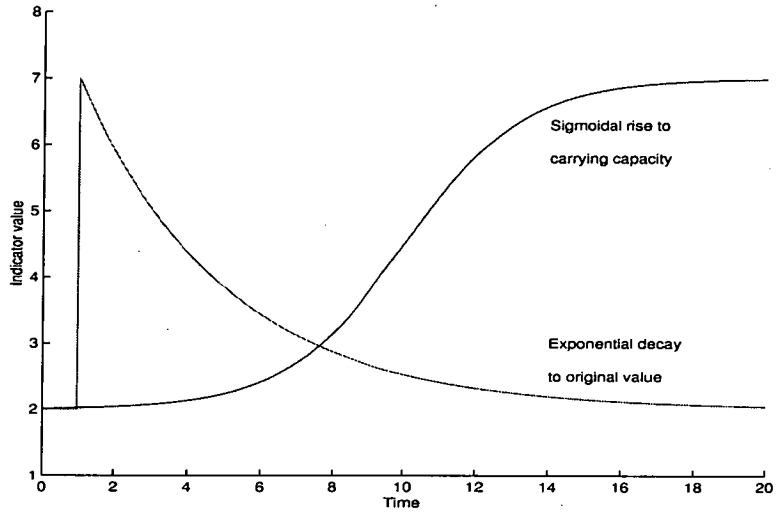


Figure 5.7 Growth and decay self-feedback profiles.

The exponential decay curve might describe the reduction in an organic waste's biological oxygen demand, C mg/L, following its discharge to a lake at time $t = t_0$, with an initial biological oxygen demand of C_0 mg/L. The decay's well known governing equation and solution are:

$$\frac{dC}{dt} = -\lambda C \qquad C(t) = C_0 e^{-\lambda t} \qquad \text{where } \lambda^{-1} \text{ is the e-folding time.}$$

The sigmoidal profile typically describes population growth (Doucet and Sloep, 1992). An example would be the colonisation of an area by an initial population of N_0 animals. The population growth is initially small but becomes rapid, following an exponential growth curve. The population growth slows as the population carrying capacity, N_∞, of the area is approached, and the overall curve is described by either of the equations:

$$N(t) = \frac{N_\infty}{1 - \left(1 - \frac{N_\infty}{N_0}\right) e^{-\lambda t}} \quad \text{or} \quad N(t) = \frac{N_\infty}{1 + e^{-\lambda(t-\tau)}},$$

where τ is the time at which the population reaches half the carrying capacity, $\frac{N_\infty}{2}$.

Modelling approach

Modelling specific feedback profiles, such as those described above, requires the indicator changes that are calculated at the end of each iteration to be subject to constraints. Figure 5.8 shows some feedback profiles which result from the repeated application of the positive and negative rule groups. For each profile, the indicator changes are constrained to move the absolute indicator value towards a predetermined value, starting from a baseline indicator value of 1.0, and an initial indicator change of +4.0.

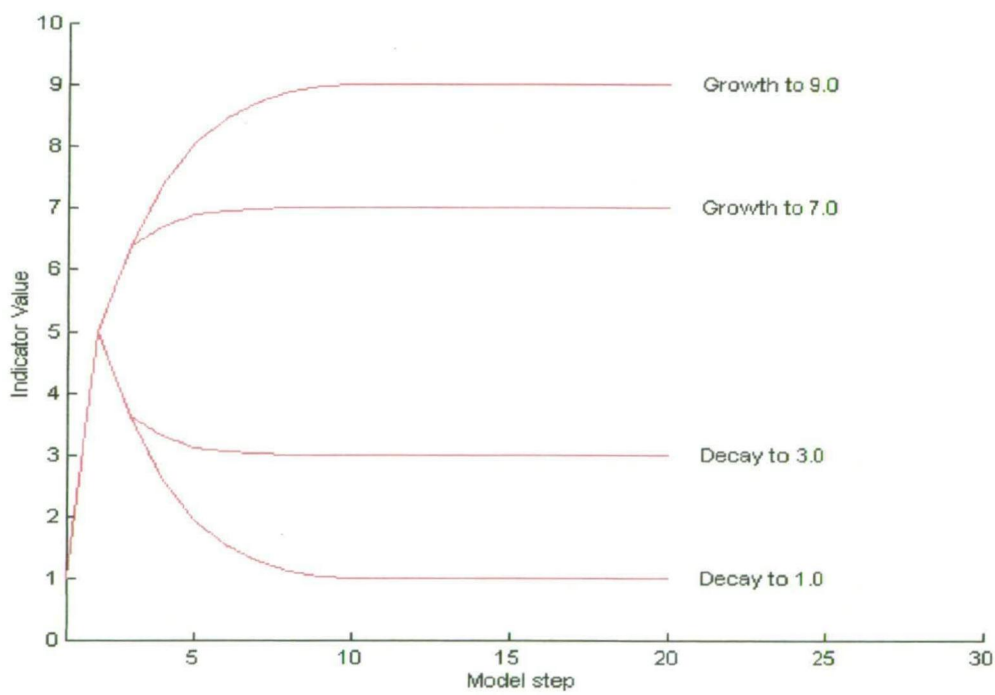


Figure 5.8 Indicator changes constrained to follow decay and growth profiles.

For the decay profiles, the indicator change for the new iteration is set to $(\Delta I)^{old} = I^{new} - I^{end}$, and the negative rule group returns the indicator back to the value I^{end}. For the growth profiles, the indicator change is set to $(\Delta I)^{old} = I^{end} - I^{new}$, and the positive rule group drives the indicator to a predetermined carrying capacity, I^{end}. Mirror images of the profiles in Figure 5.8 are obtained in the case of a negative initial indicator change.

In this modelling exercise, the indicator can drive changes to other indicators, but is itself constrained to follow a pre-set profile. In Figure 5.8, the profile is produced by repeated application of the rule groups and adjustment of the indicator changes that are input to each new iteration. The same result could be obtained by specifying the value of the indicator at each time step (iteration), which is one approach to ongoing forcing of the model when assessing projects that have ongoing impacts.

5.5.3 Two indicator interactions

Consider the socio-economic and physical environmental indicator interaction pair shown in Table 5.5. For simplicity, the interactions are deemed to have similar e-folding times.

	Socio-economic	**Environmental**
ΔSoc ^{old}	Positive One year Weight = 1	Negative One year Weight = 2
ΔEnv ^{old}	Positive One year Weight = 1	Positive One year Weight = 1
	ΔSoc ^{new}, Weight = 1	**ΔEnv ^{new}**, Weight = 1

Table 5.5 Typical interactions for pairs of indicators.

The two rule groups in the right-hand column of Table 5.5 are used to calculate the new physical environmental indicator change. The negative $\Delta Soc^{old} \rightarrow \Delta Env^{new}$ interaction describes a situation in which a socio-economic improvement comes at the expense of the physical environment, due perhaps to urban expansion. The positive $\Delta Env^{old} \rightarrow \Delta Env^{new}$ interaction describes a situation such as acid rain, in which contamination of the air leads to contamination of soil and water. The rule group weights show that the $\Delta Soc^{old} \rightarrow \Delta Env^{new}$ interaction is dominant in the calculation of the new physical environmental indicator change, and Figure 5.9 shows the decision surface for this calculation, for baseline indicator values of 5.0. (The minor fluctuations in the decision surface are too small to warrant refinement of the membership functions).

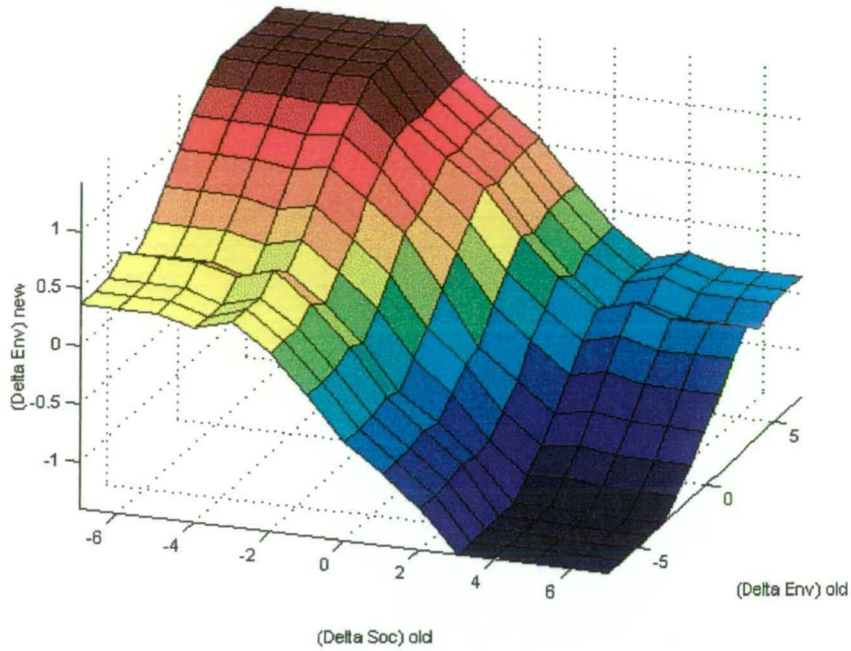


Figure 5.9 Decision surface for the calculation of $(\Delta Env)^{new}$ (the rules in the right-hand column of Table 5.5). Baseline indicators are both 5.0.

Figure 5.10 shows the predicted indicator changes for a situation in which the baseline socio-economic and physical environmental indicator values are 4.0 (poor/okay) and 9.0 (excellent) respectively, and an initial socio-economic indicator change of +2.0 is applied.

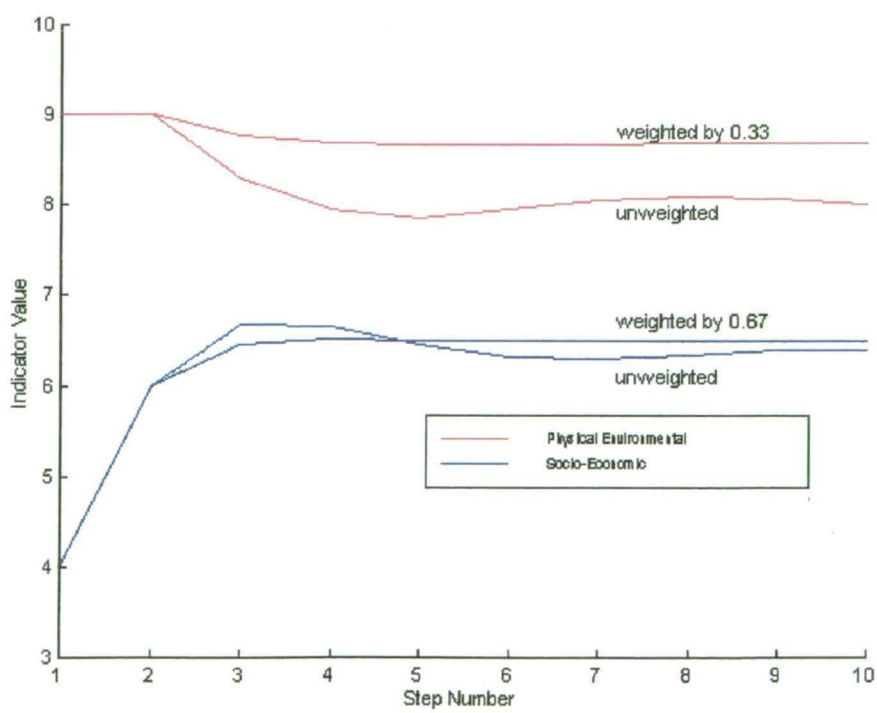


Figure 5.10 Typical socio-economic and physical environmental indicator interactions.

The final socio-economic and physical environmental indicator values are 6.35 and 8.01 respectively, and 95 % convergence to these values was achieved after 7 iterations (*i.e.* eight time steps, including the initial step). The figure also shows the model predictions with the sizes of the new indicator changes weighted as $\{\Delta Env^{new} : \Delta Soc^{new}\} = \{2:1\} = \{0.67 : 0.33\}$, giving final socio-economic and physical environmental indicator values of 6.49 and 8.67 respectively.

5.5.4 Ongoing model forcing

Consider the two indicator system described in the previous section, with the physical environmental indicator constrained to follow a predetermined decay curve. Again, the decay curve could be prescribed, but in this case it is generated by repeated applications of the negative interaction rule group, as described earlier for the case of self-feedback interactions. Table 5.6 shows the indicator system.

	Socio-economic
ΔSoc^{old}	Positive One year Weight = 1
ΔEnv^{old} Decay profile produced independently	Positive One year Weight = 1
	ΔSoc^{new} Weight = 1

Table 5.6 Interactions for a pair of indicators, with one indicator driving the system.

Figure 5.11 shows the indicator change profiles. The physical environmental indicator starts at a baseline value of 9.0, is subject to an initial change of –4.0, and has achieved 95 % of the return to its baseline value after 7 iterations (8 time steps). The $\Delta Soc^{old} \rightarrow \Delta Soc^{new}$ positive self-feedback results in the socio-economic indicator value continuing to grow in response to the final physical environmental indicator changes, reaching its "carrying capacity" after about a further 7 iterations. It does not automatically return to its original value, although it could be required to do so.

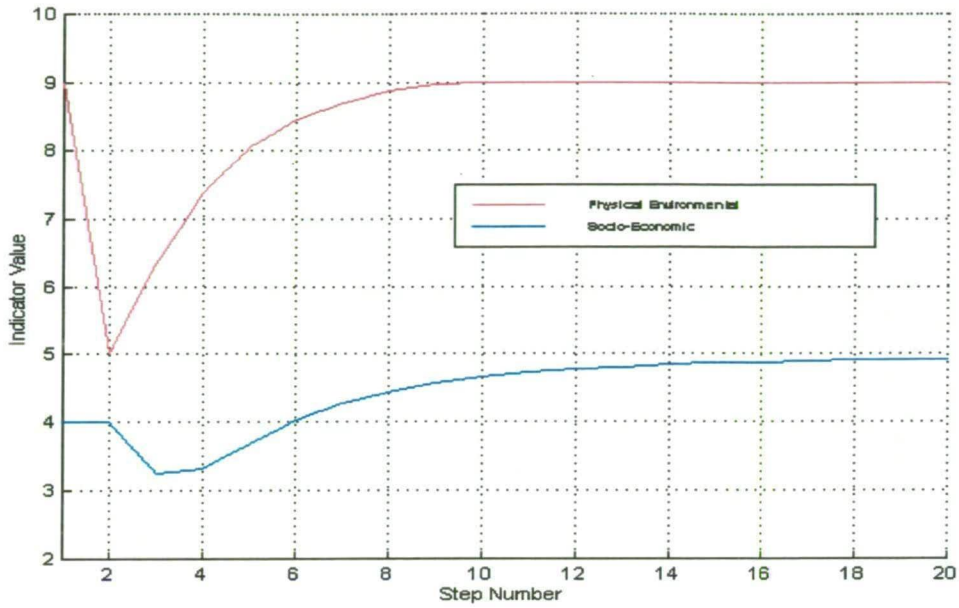


Figure 5.11 Socio-economic response to a physical environmental decay profile.

5.6 Illustration of Method

This section presents a simple illustration of the assessment method and model. The fictitious project is the construction of a harbour facility for a remote community located on an estuary. The harbour will be used by fishing vessels, cruise ships and a local industry, but its construction will involve much dredging, as shown in Figure 5.12.

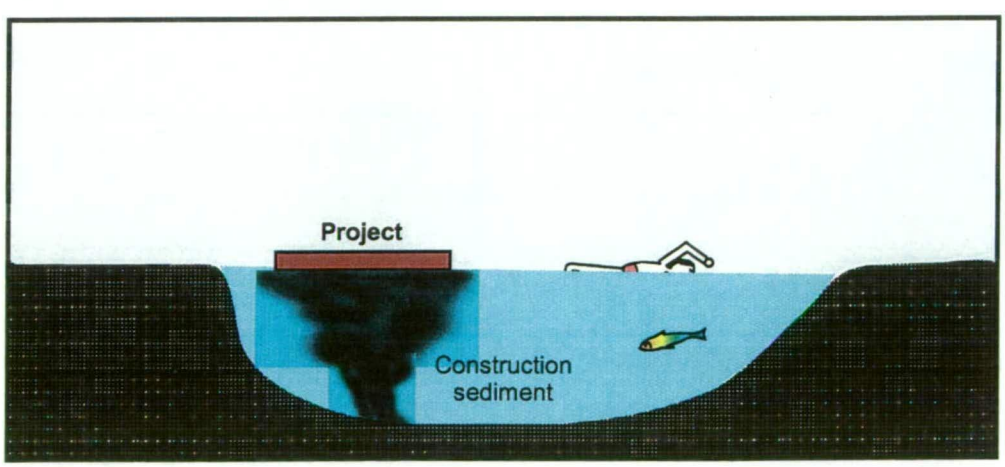


Figure 5.12 A harbour construction project in an estuary.

Common experience predicts that the sediment will degrade the river water quality, stress the aquatic ecosystems, and impair the river's use for recreation or fishing. These might be

almost insignificant changes which happen slowly, or they might be drastic changes which occur quickly. In either case, the small community will grow as a result of the employment opportunities, and this growth may be either slow or rapid. The new harbour will benefit the community, improving many of its socio-economic indicators. However, the community's growth will probably result in further adverse impacts on the water quality and biodiversity, due to increased sewage, usage of the river, community expansion and so forth.

5.6.1 Sustainability issues and indicators

For simplicity, it is assumed that the sustainability issues associated with the project can be adequately described by three indicators (indices):

- a biodiversity indicator of aquatic ecology well being (*e.g.* fish, wetlands, water fowl);
- a socio-economic indicator of local community well being (*e.g.* employment rate, housing affordability, amenities, health and education services); and
- a physical environmental indicator that describes water quality (*e.g.* sediment load).

It is further assumed that studies and surveys have determined the following baseline indicator values.

Biodiversity	9.0 (Excellent)
Socio-economic	3.0 (Poor)
Physical environment	7.0 (Good)

5.6.2 Indicator interaction rule groups

The dominant interactions between the above indicators are shown in Table 5.7. Additional interactions might exist, but each interaction is identified as either positive or negative overall. An example of a minor counter-interaction for the $\Delta Soc^{old} \rightarrow \Delta Soc^{new}$ interaction, shown in the table as a positive self-feedback, is that community growth will also result in less affordable housing, which is a negative interaction.

As discussed earlier, the rule group columns in Table 5.7 are independent of each other. For example, only the rule groups for the $\Delta Bio^{old} \rightarrow \Delta Bio^{new}$ interaction, the $\Delta Soc^{old} \rightarrow \Delta Bio^{new}$

interaction, and the $\Delta Env^{old} \rightarrow \Delta Bio^{new}$ interaction are used to calculate the new biodiversity indicator change, ΔBio^{new}.

	Biodiversity	Socio-economic	Environmental
ΔBio^{old}	Increased flora & fauna leads to more flora & fauna, moving toward the river's carrying capacity. One year. Weight = 1	Better fauna & flora improves bird watching, fishing, and swimming. One year. Weight = 1	Larger wetlands remove more contaminants. 3 months. Weight = 2
ΔSoc^{old}	Growth of community destroys wetland habitat. One year. Weight = 1	More employment and wealth improves business and community support services. 3 months. Weight = 4	Community growth produces more sewage and storm water runoff, which adversely impacts water quality. One year. Weight = 1
ΔEnv^{old}	Degradation of water quality will adversely impact marine grass and other aquatic ecology. 3 months. Weight = 3	Better water quality improves recreational & resource potential. One year. Weight = 1	Water contaminants will degrade river bed sediment quality. One year. Weight = 2
	ΔBio^{new} Weight = 1	ΔSoc^{new} Weight = 1	ΔEnv^{new} Weight = 1

Table 5.7 Dominant indicator interactions, time scales and weights. The positive and negative interaction rule groups are shaded and unshaded respectively.

5.6.3 Time scales and weights

Table 5.7 also shows the indicator interaction e-folding times and rule group weights. For convenience, these are assumed to be the same as those used in the Mount Lyell case study (Chapter 6), which has an identical pattern of indicator interactions. In practice, they would be assigned following an assessment of the situation being modelled.

Interaction time scales

Interaction time scales depend on the responding indicators, not on the forcing indicators, nor on the project. For example, in the $\Delta Env^{old} \rightarrow \Delta Bio^{new}$ interaction, the e-folding response time (3 months) of the aquatic ecology to a change in water quality is measured with respect to a sudden change in water quality change, but does not depend on the magnitude of the change. The e-folding time for the overall system will be comparable to the e-folding time of its slowest interaction, about one year in the case of this project. The better the understanding of the interactions and their response times, the more precise will be the specification of the overall time scale.

Rule group weights

In the *MATLAB* software, a weight is an intrinsic part of every fuzzy rule, the default being that all rules are equally weighted. The weights which scale the relative sizes of the new indicator changes are applied at the completion of each iteration, following defuzzification of the indicator change values.

Two factors should be considered in assigning the rule group weights.

1. The natural interaction strengths.

2. The relative interaction time scales. Rapid interactions should be weighted more heavily than those which occur more slowly. Each iteration is equivalent to a time step, and the change in an indicator with a fast response time will be greater over this time step than the change in an indicator with a slow response time.

Two interactions in Table 5.7 are heavily weighted, for both of the above reasons. The $\Delta Env^{old} \rightarrow \Delta Bio^{new}$ interaction is dominant in the calculation of the new biodiversity indicator change, due to the typically strong dependence of biodiversity on the quality of the physical environment. The $\Delta Soc^{old} \rightarrow \Delta Soc^{new}$ self-feedback is dominant in the calculation of the new socio-economic indicator change, since communities grow primarily in response to improvements in employment, health services, education etc.

It is often helpful to model pairs of indicator interactions on their own, as was done earlier in this chapter, to better understand the interactions, and to ensure that rule group weights are correctly assigned.

The assignment of weights for the new indicator changes depends on the situation being modelled. For example, the river's biodiversity might be quite insensitive to changes in physical environment quality, or to disturbance by community growth. Placing a low weight on the ΔBio^{new} value will scale it down compared to the other indicator changes. Changing the weights of the rule groups which contribute to the calculation of ΔBio^{new} will not give the same result, since the size of the new indicator change depends only on the range of the output indicator change membership functions, not on how many rule groups are used in the calculation, nor on the rule group weights.

5.6.4 Model forcing

An overall system e-folding time of one year has now been established, so the system should be within 5 % of its new equilibrium in about three years ($e^{-3} \approx 0.05$). Preliminary model runs show that 95 % of the indicator changes due to indicator interactions are calculated after 7 iterations (8 time steps), which is usually the case for the present model. Each time step is thus about 4½ months.

The primary impacts are associated with the harbour construction period, which is expected to be about 9 months. To a reasonable approximation, the model can thus be driven by an initial impulse over a 9 month first time step, provided that the size of the initial indicator changes is consistent with project impacts over 9 months, not 4½ months.

- The initial physical environmental indicator change is set to be -2.5, corresponding to an expected (if somewhat drastic) decrease in river water quality from 7.0 (Good) to 4.5 (Okay) over the 9 month construction period.

- The initial socio-economic indicator change is set to +3, which corresponds to the direct and immediate community benefits associated with the project. Follow-on benefits are calculated by model as additional changes, primarily due to the $\Delta Soc^{old} \rightarrow \Delta Soc^{new}$ self-feedback.

- Table 5.7 shows that a physical environmental indicator change will produce a change in the biodiversity indicator on an e-folding time scale of 3 months. This is smaller than the 9 months over which the initial changes occur, so an initial biodiversity indicator change of −1 is specified, even though the project is assumed not to directly impact the biodiversity.

5.6.5 Model predictions

Table 5.8 and Figure 5.13 show the model predictions. The indicator changes demonstrate an interplay between the sustainability themes which is often associated with development projects, whereby the socio-economic indicator increases at the expense of the physical environment and biodiversity indicators.

Indicator	Baseline value	Initial change	Interaction changes	Final value
Biodiversity	9.0	- 1.0	-2.09	5.91
Socio-economic	3.0	+ 3.0	+0.69	6.69
Physical environment	7.0	- 2.5	-1.88	2.62

Table 5.8 Model indicator change predictions.

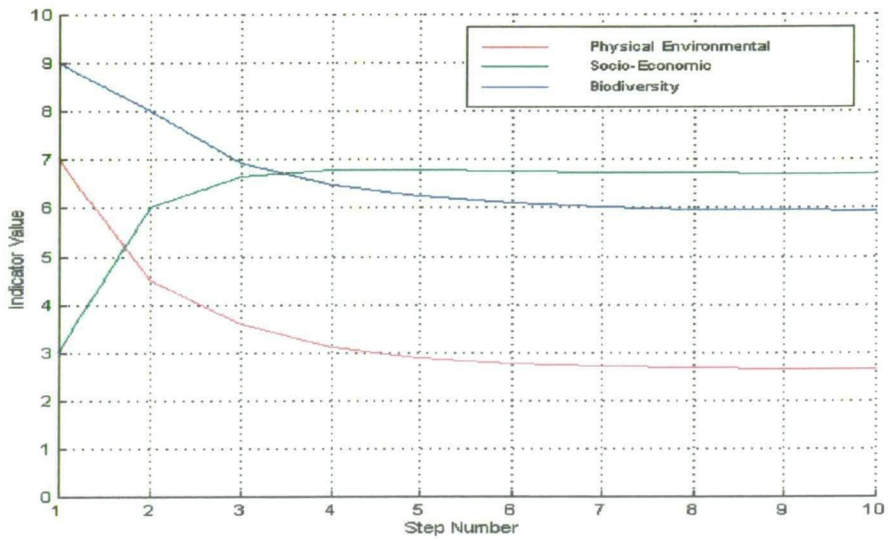


Figure 5.13 Model predictions, with typical interplay between sustainability themes.

5.6.6 Sensitivity tests

Solution convergence

The first set of sensitivity tests examines the convergence of predicted indicator changes. Figure 5.14 (top) shows a typical simulation in which the iterative calculation process is truncated using an indicator change size tolerance of $\varepsilon = 0.1$. Figure 5.14 (bottom) shows the same simulation allowed to iterate to steady state.

Comparison of the two figures shows that using a stopping criterion in the form of the tolerance is reasonable, and that the iteration converges smoothly. Also, the overall changes due to indicator interactions are of the same magnitude, or less than, the initial indicator changes, which confirms this model design feature.

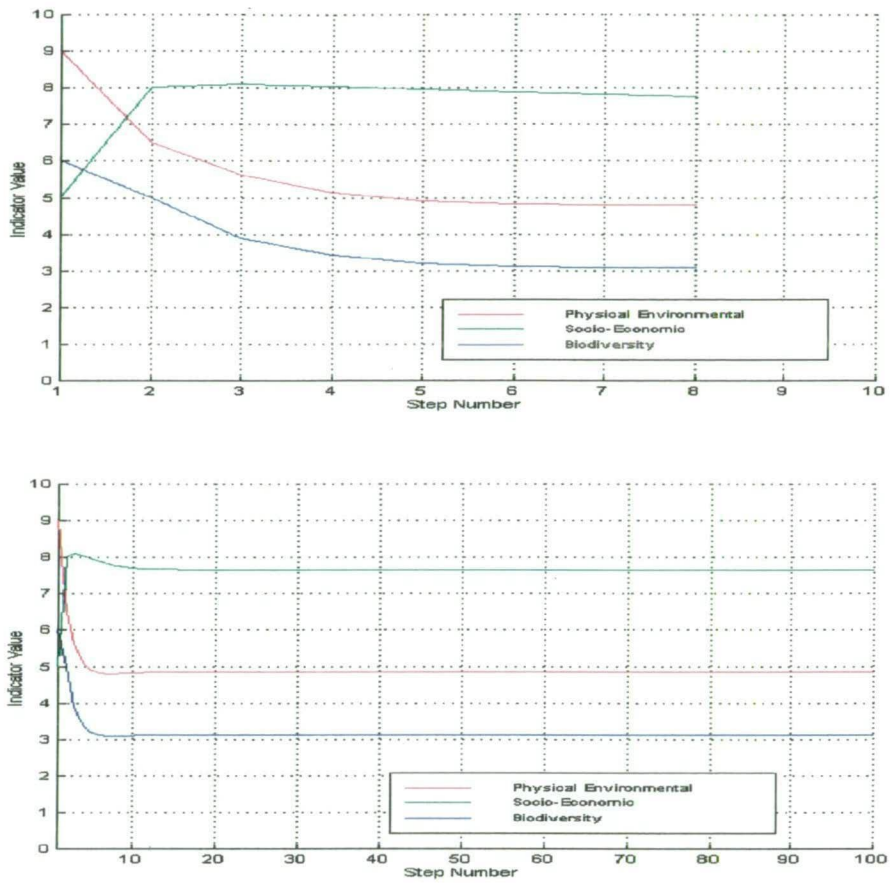


Figure 5.14 Top: convergence based on tolerance (size of indicator changes). Bottom: iteration to steady state.

Solution independence

The second set of sensitivity tests examines whether the indicator change predictions are independent of the baseline indicator values. Some problems are associated with a limited number of solutions. For example, the non-linear equation $z^4 = 1$, has only four roots, and an iterative calculation should always find one of these solutions.

The model simulations shown in Figures 5.13 and 5.14 are driven by the same set of initial indicator changes, but have different baseline indicator values. The simulations result in quite different predictions, suggesting that the model is well behaved with respect to baseline indicator values changes, an assertion supported by the case studies presented in Chapters 6 and 7.

Perturbation tests

Table 5.9 shows the results of tests to examine the sensitivity of the model predictions with respect to perturbations in the baseline indicator values. The table confirms that the model

predictions depend on the baseline indicator values in a smooth fashion. It also shows that small changes in the baseline indicator values produce small changes in the model predictions, which is sensible behaviour. If the small changes in the baseline values are doubled, then the corresponding changes in the model predictions also roughly double (*i.e.* the solution is locally linear).

	----------Indicator values----------		
Indicator	**Baseline**	**Final**	**ΔFinal**
Bio	3	2.312	-
Soc	8	8.955	-
Env	2	3.986	-
Bio	3.1	2.289	0.023
Soc	7.9	8.901	0.054
Env	2.1	4.017	0.031
Bio	3.2	2.258	0.054
Soc	7.8	8.852	0.103
Env	2.2	4.037	0.051

Table 5.9 Sensitivity tests with respect to baseline indicator perturbations.

5.7 Discussion

The principal strengths of the assessment method are that it:

- organises sustainability issues into a classification which readily fits with the way engineers and planners think about projects, and commission specialist studies;

- assesses sustainability impacts in terms of indicator changes, which accords with State of the Environment and Local Agenda 21 initiatives; and accepts indicator values on a practical 0-10 scale that facilitates the use of "best-guess" input, and the interpretation of the indicator values by planners; and it

- uses a simple but powerful modelling approach that overcomes several of the barriers to a traditional modelling approach.

A limitation of the method is that few sustainability visions defined in terms of indicators exist at present. However, this situation is changing rapidly, and the assessment method will become easier to use as strategic resource management visions are developed, and as geographic information systems and environmental databases improve.

Another limitation is that the fuzzy model is quite crude. This is a necessary consequence of trying to model a system of indicators which have interactions that are not fully understood, and of modelling with "best-guess" input. The model predictions can be adjusted using weights, but the modeller must be aware of the adage "garbage in equals garbage out".

The crude nature of the model is a less important limitation when the assessment method is used as a tool for comparing the consequences of different project options. In this case, it may be possible to use just one or two fingerprint indicators to describe each sustainability theme, and still gain useful insight regarding the preferred option. Chapter 8 examines selection and optimisation of the preferred option, with consideration of constraints such as cost and technical difficulty.

The assessment method demands a fair understanding of the way in which a project can influence sustainability issues, and the nature of the dominant interactions between the indicators that describe those issues. However, if this understanding is not developed to the point that we can carry out sustainability impact assessments, then sustainability will remain a semi-quantifiable resource management and planning objective. Until the problem of lack of knowledge is resolved, it will remain an underlying flaw in any modelling approach.

The following assessment exercises should be carried out, if appropriate:

- Examine how the project will change the sustainability aspects of the local area compared to larger regions. For example, a new industrial operation may provide socio-economic benefits for a large region, but have severe adverse local consequences.

- Examine the effect of altering the project to produce a different model forcing. For example, the project might be scaled up or down, cleaner production technology might be introduced, or environment protection measures and biodiversity management measures might be changed.

- Run sensitivity tests to determine the importance of the various indicators regarding the model predictions, and thus to the subsequent planning decision. This knowledge can be used to design baseline studies to better understand an indicator, to design appropriate monitoring programs, and to examine the need for use of the precautionary principle.

Some projects will result in certain indicators improving at the expense of others, in spite of impact mitigation measures. In these cases, a decrease in an indicator might be tolerated if the overall sustainability vision for the region is maintained, since a regional vision usually provides for heavy industrial zones as well as for wilderness areas. Alternatively, it may be possible to introduce measures to off-set the local adverse consequences of the project. For example, in an air quality non-attainment area, reductions from an existing emission source within the airshed may be required in order to permit a new emission source.

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6.0 PRIMARY INDUSTRY CASE STUDIES

6.1 Introduction

Chapters 6 and 7 present case studies that further illustrate the sustainability assessment method described in Chapter 5, following the four basic steps.

- Identify the sustainability issues associated with the project.
- Define a concise set of indicators that describe the sustainability issues, and estimate the baseline indicator values.
- Prepare the model input, specifying the indicator interactions, and the model forcing.
- Run the model and examine the indicator change predictions.

Specification of the indicator interactions means identifying the dominant interaction processes, the rule group weights, and the indicator change weights. Assigning weights requires consideration of the natural strengths and speeds (e-folding times) of the interactions.

6.2 Mount Lyell Mining Operations

6.2.1 Background

Figure 6.1 shows the West Coast of Tasmania. Queenstown, the regional population centre, is a town that was established in large part to support mining operations at nearby Mount Lyell. The small coastal town of Strahan lies 25 km west of Queenstown, at Macquarie Harbour, and was originally associated with an infamous penal facility. The region is quite isolated, and was linked to the rest of Tasmania only by sea and rail transport before the Lyell Highway from south Tasmania was opened in 1932.

The history of Tasmania's West Coast communities is documented by Blainey (1954), and reviewed in an environmental impact context by SDAC (1995), McQuade et al. (1995), and Thompson and Brett (1995). Prior to the 1880s, the region was essentially uninfluenced by

human activities. Mining in the area dates from the discovery in 1883 of the "Iron Blow" copper deposit at Mount Lyell, and early mining operations followed a frontier economics ethic, with little regard for environment protection. By 1900, Mount Lyell had become the largest copper mine in the British Empire, and the Tasmanian *Environment Protection Act (1973)* was introduced far too late to mitigate the environmental degradation that is the legacy of the region's mining history.

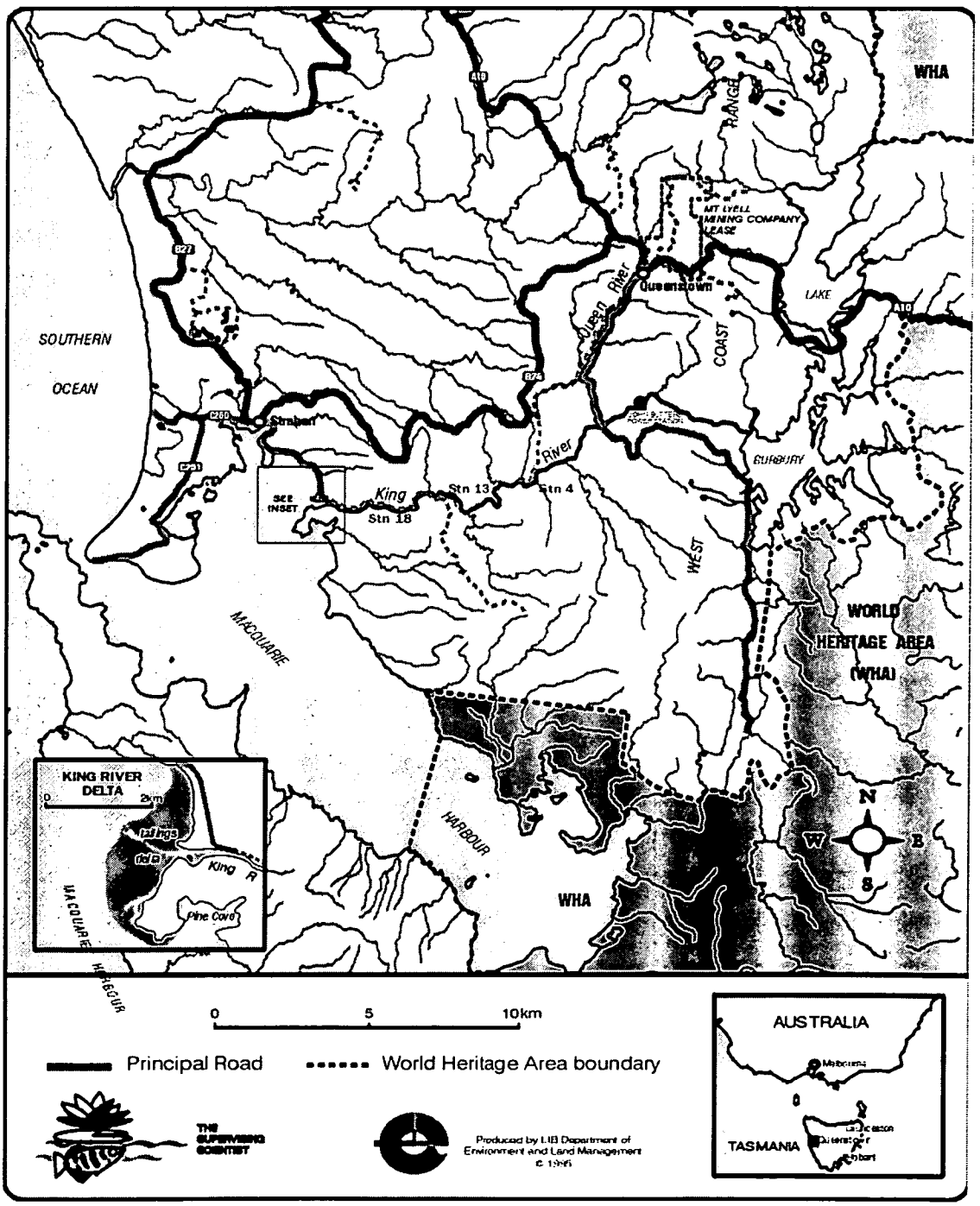


Figure 6.1 Tasmania's West Coast, showing the location of the Mount Lyell mine. (courtesy of the Dept. of Environment and Land Management).

Mining operations at Mount Lyell were scaled down after 1970, and the mine closed in late 1994, having produced over 1.3 million tonnes of copper, 750 tonnes of silver, and 45 tonnes of gold, worth over A$4 billion in 1995. The Mount Lyell Remediation Research and Demonstration Program was established in 1995, to study environmental damage in the Queenstown region, and to design a remediation strategy. The program was jointly managed by the Federal and Tasmanian Governments, and comprised 14 projects. Koehnken (1997) summarises the research findings, and sets out a basis for a remediation plan which targets the primary pollution sources, principally ongoing acid drainage from the Mount Lyell lease site.

Several companies expressed interest in continuing the mining lease, and Copper Mines of Tasmania Pty Ltd (CMT) became the new mine operator, indemnified by the *Copper Mines of Tasmania (Agreement) Act (1994)* for both existing and ongoing environmental harm caused by previous mining activities. CMT reopened the mine in late 1995, and the company's mining operations are guided by an Environmental Management Plan within the context of the above agreement (Thompson and Brett, 1995).

Three sustainability impact assessments are considered.

1. ***Mine start-up.*** This assessment is of the impact of the initial period of mining, which started in the mid-1880s.

2. ***1995, mine open.*** This assessment examines the expected impacts of continued mining operations by CMT.

3. ***1995, mine closed.*** This scenario examines the impacts which would have occurred if the mine closure in late 1994 had been permanent.

The geographic area is the environs of Mount Lyell (about 50 km^2), together with the Queen River, the lower King River and Macquarie Harbour. Queenstown is included, but the town of Strahan is excluded. As discussed below, the characteristic response time of the system of indicators means that each assessment is associated with a time frame of some 10+ years.

6.2.2 Sustainability issues and indicators

Table 6.1 sets out the sustainability issues and indicator areas associated with the mining operations at Mount Lyell, based on a review of SDAC (1995), McQuade et al. (1995), and Thompson and Brett (1995); and also on site visits and discussions with Dr Alan Robertson, CMT's environmental manager (see Carter et al., 1998).

Theme/indicator	Primary considerations
Biodiversity	Aquatic ecology of the Queen River, the lower King River, and Macquarie Harbour. Habitat extent & quality in the 50 km^2 area centred on Queenstown, and along the banks of the Queen River and the lower King River.
Socio-economic	Queenstown's population, average income, employment, community support services (*e.g.* health, education, amenities), and access to other population centres.
Physical Environment	Water quality. Same domain as for aquatic ecology. Soil quality. Same domain as for habitat.

Table 6.1 Sustainability issues and indicators for Mount Lyell mining operations.

Each sustainability theme is described by a single fingerprint indicator since, at least to a first approximation, the component aspects of each theme respond in similar ways to the mining activities. The condition of Macquarie Harbour is a surrogate for any impacts in the Southern Ocean (such impacts were not studied by the 1995 research program). The 0-10 scales for these indicators are in accord with the usual definitions of *Bad* to *Excellent* as these definitions pertain to each sustainability theme. For example, a *Bad* physical environmental indicator value describes soil and water quality that is in a critical condition.

1880s - 1900s indicator values

Table 6.2 shows the estimated indicator values in the mid-1880s and the early 1900s. Prior to the start of mining activities, the physical environmental quality of the region would have been excellent, and the biodiversity would have been similar to the temperate rainforest conditions found today in the nearby World Heritage wilderness areas. The few people who lived in the region had poor access to education, health or other community support services.

Biodiversity	Socio-economic	Physical environment
1880s 9 (Excellent) Near wilderness values.	1880s 3 (Poor) Small, remote community with few support services.	1880s 9 (Excellent) Near wilderness values.
1900s 1 (Bad) No life in the Queen River and the lower King River. Macquarie Harbour ecology is impoverished. Vegetation is destroyed in the vicinity of Queenstown, and along the river banks.	1900s 7 (Good) Queenstown is a prosperous and stable community of about 6,000 people. However, the town is remote from other population centres.	1900s 1 (Bad) Waters are acidic, and contaminated with metals. The river banks are smothered with tailings, and a delta has been created in Macquarie Harbour. Severe soil erosion in the region.

Table 6.2 Estimated indicator values, mid-1880s and early 1900s.

By the early 1900s, Queenstown had become a prosperous community of about 6,000 people, albeit still with poor links to other population centres. However, the physical environmental and biodiversity indicators had been drastically reduced. Mining activities had produced the lunar landscape which still characterises the area (see Figure 6.2), and had severely impacted both the water quality and the biodiversity of the Queen River, the lower King River, and Macquarie Harbour, where a delta of copper-rich tailings was developing.

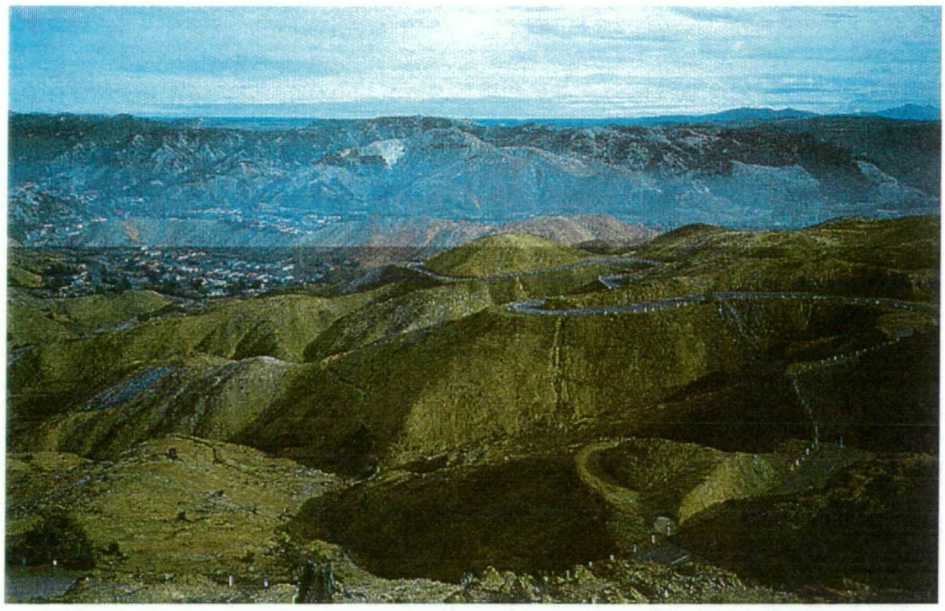


Figure 6.2 Queenstown's lunar landscape: well established by the early 1900s.

1900s - 1995 indicator changes

When CMT reopened the mine in late 1995, the sustainability indicator values are estimated to have changed as shown in Table 6.3.

Theme / Indicator	1900s	1995
Biodiversity	1 (Bad)	2 (Bad/Poor)
Socio-economic	7 (Good)	5 (Okay)
Physical environmental	1 (Bad)	1 (Bad)

Table 6.3 Estimated indicator changes early 1900s to 1995.

After the early 1900s, the environmental impact of the mine reduced as mining operations moved underground, smelting ceased, and environmental management improved. The Lyell Highway from Hobart opened in 1932, and the transport infrastructure serving Queenstown from the north was upgraded. Overall, it is considered that the physical environmental indicator in the environs of Mount Lyell did not change significantly, remaining at 1 (Bad), while the biodiversity indicator increased slightly from 1 (Bad) to 2 (Bad/Poor), as some limited revegetation occurred.

In 1970, Queenstown's population was still over 5,000 people, with some 1,200 people directly employed by the mining industry. Mining operations were subsequently scaled down, and the town's population declined to about 3,000 people in 1994, with only 330 direct mine employees. The mine's closure in late 1994 produced a further population decline to about 2,500 people in 1995, and SDAC (1995) identified other impacts of mine closure as increased unemployment, reduced school enrolments, a reduction in business activity, an increase in vandalism, a transfer of dependence from industry to government, a period of grieving, and reduction in community self-esteem. However, these impacts were ameliorated by expectation of the mine being reopened by CMT, and because improved transport infrastructure had lessened the community's isolation. It is estimated that the socio-economic indicator had decreased from 7 (Good) to 5 (Okay) by 1995.

6.2.3 Indicator Interactions

Table 6.4 sets out the dominant indicator interactions, together with their estimated e-folding times and rule group weights. The new indicator changes, $\{\Delta Bio^{new}, \Delta Soc^{new}, \Delta Env^{new}\}$ are unweighted (*i.e.* equally weighted), and are not constrained in any way.

	Biodiversity	Socio-economic	Environmental
ΔBio^{old}	Positive: Weight = 1 4 years. Destruction of vegetation adversely impacts associated fauna.	Positive: Weight = 1 4 years. Degraded ecosystems impact community's natural resource base.	Positive: Weight = 2 4 years. Destruction of vegetation results in soil erosion.
ΔSoc^{old}	Negative: Weight = 1 2 years. Development destroys and fragments habitat.	Positive: Weight = 4 1 year. Mining wealth results in improved community services and amenities.	Negative: Weight = 1 2 years. Development adversely impacts the environment (*e.g.* soil contamination).
ΔEnv^{old}	Positive: Weight = 3 1 year. Water pollution impacts aquatic ecosystems. Acid fumes destroy vegetation, and erosion prevents revegetation. Tailings smother river bank vegetation.	Positive: Weight = 1 4 years. Degraded environment reduces community's natural resource base (*e.g.* drinking water, fishing, bush walking).	Positive: Weight = 2 4 years. Smelter emissions acidify soil & water. Tailings contaminate water and soil, and create delta in Macquarie harbour.
	ΔBio^{new} Weight = 1	ΔSoc^{new} Weight = 1	ΔEnv^{new} Weight = 1

Table 6.4 Dominant interactions, and their estimated e-folding times and weights. Positive and negative interactions are shaded and unshaded respectively.

The interaction e-folding times are only rough estimates. Considering the first column, the $\Delta Env^{old} \rightarrow \Delta Bio^{new}$ interaction is expected to occur more rapidly, and to be stronger, than the other interactions which contribute to the calculation of ΔBio^{new}. Similar comments apply to the $\Delta Soc^{old} \rightarrow \Delta Soc^{new}$ interaction in the second column. In the third column, the $\Delta Soc^{old} \rightarrow \Delta Env^{new}$ interaction is often the most important in the calculation of ΔEnv^{new}. However, for this project, the $\Delta Env^{old} \rightarrow \Delta Env^{new}$ and the $\Delta Bio^{old} \rightarrow \Delta Env^{new}$ interactions are likely to be even more significant, due respectively to soil acidification from smelter emissions, and to soil erosion once hill side vegetation is removed. The rule groups in this third column are thus weighted in the ratio {2:1:2} = {0.4 : 0.2 :0.4}.

The system of indicators described by Table 6.4 will have an overall e-folding time which is roughly the same as that of the slowest interactions, *i.e.* 4 years. The system is thus expected to achieve 95 % of its new equilibrium some 12 years (three e-folding times) after cessation of model forcing. Preliminary model runs show that this situation is achieved after about seven iterations, so each iteration corresponds to about 20 months. This is only a rough calculation, but it is sufficient for a first-pass sustainability assessment.

6.2.4 Model Forcing

Mining start-up assessment

After commissioning of the Mount Lyell mine, most of the factors contributing to the socio-economic indicator improved rapidly as the local community benefited from the work and prosperity brought by the mine. The physical environment and biodiversity indicator changes were highly negative, since the mining impacts were not mitigated by environment protection or biodiversity management measures. The principal impacts derived from surface mining operations, support road and rail infrastructure and urban development, timber harvesting, acid gas smelting emissions, acid mine drainage, and mine tailings disposal. Over about 20 years, by the early 1900s, Queenstown had grown to become a stable community, but the biodiversity and physical environmental indicator values had both reduced to the *Bad* range.

A realistic model forcing approach would be to recognise that the mining activities had an ongoing impact, and thus to specify both initial indicator changes over the first 20 months, and additional indicator changes after each iteration (*i.e.* each further 20 month period). The size of the additional indicator changes would diminish, since the model forcing at each time

step (iteration) reflects the impact of the project over the 20 month time step with respect to the updated absolute indicator values, not the original baseline indicator values. By the early 1990s, the mining operations did not produce significant further indicator changes.

In this first case study, however, the impact of mining activities is approximated as a strong impulse forcing, with indicator changes driven only by a set of initial indicator changes. The changes are envisaged as occurring over a nominal 10 year period, and the indicator interactions then play themselves out over an additional 10+ years.

1995 assessments

The first 1995 assessment considers the impact of continued mining operations. CMT is working with the State Government on a range of environment protection and biodiversity improvement initiatives, and the mine is operated within the framework of an environmental management plan. An acid drainage neutralisation and copper recovery system is proposed (Koehnken, 1997), new tailings basins have been constructed, and revegetation projects are underway, particularly along the river banks. The mine continues to benefit Queenstown's socio-economy, with ongoing employment for local people.

The second assessment examines the hypothetical scenario in which mining operations ceased permanently in 1994. The State Government would have undertaken some environment protection initiatives anyway, since the impact of an abandoned copper mine is significant, due to ongoing acidic, metal-laden drainage from the mine site. Such problems occur anywhere a sulphidic ore or waste rock is subject to oxidation (Waldichuk, 1987). However, the lack of an active environmental management plan would likely have resulted in improvements being limited compared to the mine continuation scenario. Queenstown's socio-economy would also suffer from the lack of mining activity, as envisaged by SDAC (1995), although the impact would be cushioned by tourist industry benefits.

The physical environmental and biodiversity indicator interactions and weights, shown in Table 6.4, are assumed to be the same for all three assessments. However, the $\Delta Bio^{old} \rightarrow \Delta Soc^{new}$ and the $\Delta Env^{old} \rightarrow \Delta Soc^{new}$ interactions for the 1995 assessments may have changed slightly, since local opinion holds (probably quite correctly) that revegetation would reduce the value of the Queenstown hills as a tourist attraction.

The model forcing for the two 1995 assessments is specified as sets of initial indicator changes over the nominal five year period 1995-2000. The model predictions will relate to

the year 2010 and beyond and, while they will not be correct in absolute terms, they should allow a clear conclusion regarding which option is preferable.

Table 6.5 summarises the initial indicator changes used for the three assessments.

	Biodiversity	*Socio-economic*	*Phys. Environment*
1880 assessment	-5.0	+3.0	-5.0
1995 mine open	+1.5	+1.0	+2.5
1995 mine closed	+1.0	-1.0	+0.5

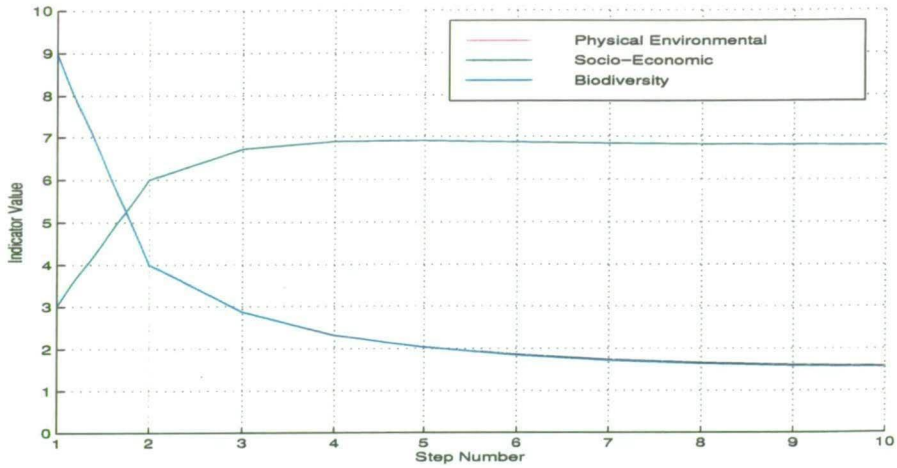
Table 6.5 Estimated initial indicator changes, over a nominal 10 year period for the 1880 assessment, and a nominal 5 year period for the 1995 assessments.

6.2.5 Model Predictions

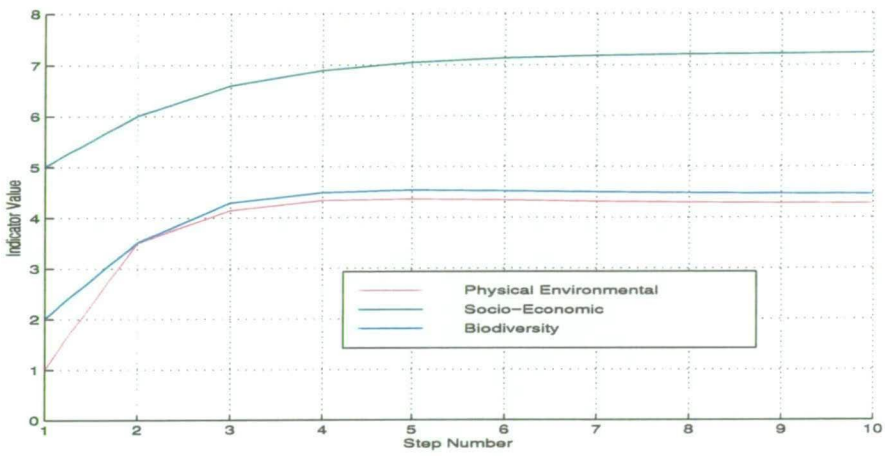
Figure 6.3 and Table 6.6 set out the model predictions for the three assessment exercises. The mine start-up impact assessment confirms the ability of the model to handle extreme indicator values, and Table 6.6 shows that there is quite good agreement between the estimated and predicted indicator values. The biodiversity and physical environmental indicators reach 95% of their final values after 7 iterations. The socio-economic indicator rises to 6.91, then falls to within 5% of its final value (6.78) after 6 iterations.

Considering the two 1995 assessments, the predicted indicator values are plausible, but cannot be verified since they relate to the year 2010 and beyond. However, the assessment model would have to be very wrong indeed to change the clear conclusion, for each sustainability theme, that the continuation of mining operations is preferable to mine closure. Moreover, a properly managed mining operation provides a funding window of opportunity in which long term environmental improvement strategies can be implemented.

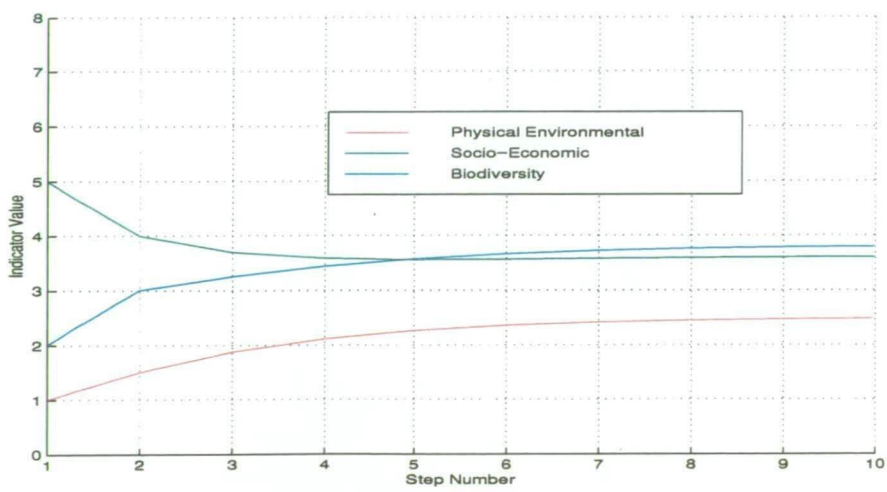
A more detailed assessment exercise might consider the sustainability influence of mining operations beyond the geographic area considered herein. The mine's metal production and employment benefit Tasmanian and Australia as a whole, while support facilities such as transport infrastructure also have socio-economic and environmental impacts beyond the environs of Mount Lyell. Also, the coastal community of Strahan has developed mariculture industries which may be put at risk by ongoing water pollution, while the establishment of nearby World Heritage wilderness areas in 1982 has resulted in new eco-tourism businesses.



Mid-1880s to 1900s. Physical environmental & biodiversity indicator changes are the same.



1995 to 2005 and beyond, mine open.



1995 to 2005 and beyond, mine closed.

Figure 6.3 Indicator change predictions. See text for discussion of time frames.

Indicator	Mid-1880s	Early 1900s		1995	2010 and beyond	
		Expected	*Model*		*Mine open*	*Mine closed*
Biodiversity	9 Excellent	1 Bad	1.52 Bad	2 Bad/Poor	4.44 Okay	3.80 Poor
Socio-economic	3 Poor	7 Good	6.78 Good	5 Okay	7.23 Good	3.62 Poor
Physical environmental	9 Excellent	1 Bad	1.54 Bad	1 Bad	4.26 Okay	2.49 Poor

Table 6.6 Summary of sustainability indicator values.

6.3 Forestry Operations in North-West Tasmania

6.3.1 Introduction

The forested area of Tasmania in the early 1800s, at the time of European colonisation, is estimated to have been 40,450 km^2, about 59 % of the State's 68,050 km^2 area. By 1993, the forested area had decreased to about 33,170 km^2, just under 50 % of the State's area (Forestry Commission 1994; Kirkpatrick et. al, 1995; SDAC, 1996). Forestry Tasmania's most recent estimate is that the remaining area of native forest, not including plantation forest, is 32,040 km^2 (John Sulikowski, pers. comm., October 1998).

This case study assesses the sustainability of several forestry operation scenarios in north-west Tasmania. Figure 6.4 shows the Circular Head forest district, which corresponds to the Circular Head municipality; and the Murchison forest district, which broadly corresponds to the Waratah-Wynyard, King Island and West Coast municipalities. The two forest districts have a combined area of 20,465 km^2, and the municipalities that they encompass had a total population of 30,400 people in 1997, about 6% of the State's population. The main towns of Burnie, Smithton, Devonport, and Ulverstone are all located on the State's north coast.

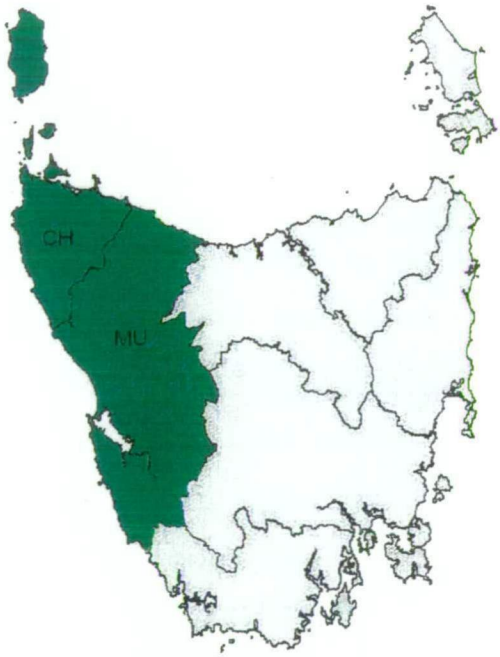


Figure 6.4 The Circular Head and Murchison Forest Districts.

The regional economy is based on the primary industries of agriculture, dairy farming, forestry, mining and mineral processing, and fishing. Eco-tourism is also a significant source of revenue. The region has extensive forest cover, with high quality biodiversity and physical environment (Forestry Commission, 1997; 1998a). Figure 6.5 shows the broad forest types that characterise the north parts of the Murchison and Circular Head forest districts region. The cool temperate rainforest is very different from the warmer climate rainforest found on mainland Australia, and has special conservation value, with myrtle, leatherwood, celery top pine, and sassafras forest communities.

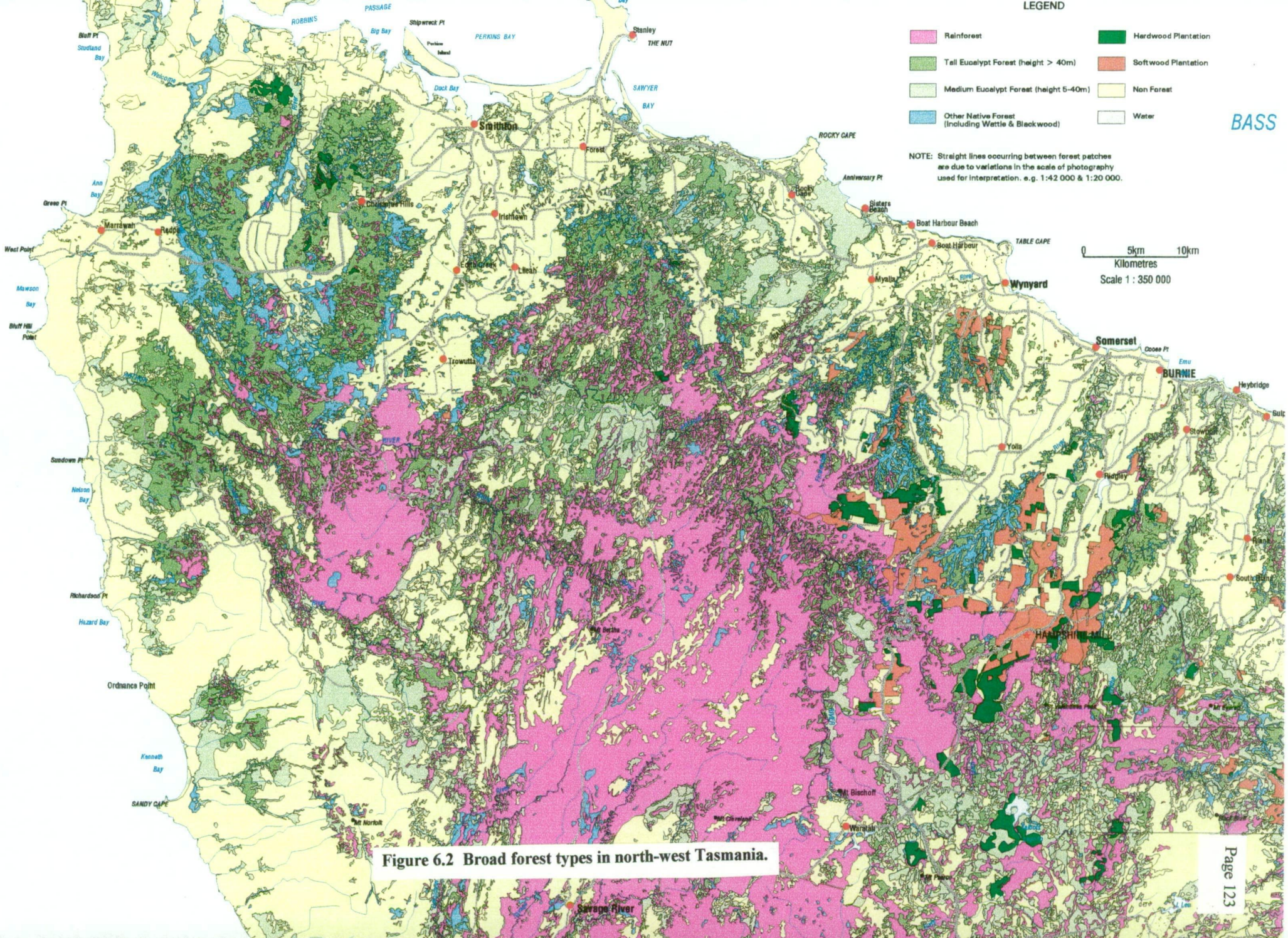


Figure 6.2 Broad forest types in north-west Tasmania.

Three comparative sustainability assessments are presented, with a baseline year of 1990 that predates construction of the Hampshire wood chip mill, and increased wood-chip production quotas (ETS 1993a; 1993b). In the planned forestry scenario, expected indicator values are compared to predicted values in the year 2010.

Planned forestry operations

This scenario examines the impact of proposed timber harvesting and wood processing, carried out within a framework of sustainable resource management. The scenario assumes effective environment protection and biodiversity conservation measures, and minimisation of adverse socio-economic aspects.

Frontier economics scenario

This scenario examines a similar scale of timber harvesting and wood processing to the planned forestry scenario, but carried out according to a frontier economics philosophy. The potential consequences of this approach include loss of the timber resource, habitat destruction and fragmentation, soil erosion, water quality degradation, and loss of forest recreation and eco-tourism potential.

Deep ecology scenario

This scenario assumes that all the regional forests are closed to timber harvesting, with conservation values being placed ahead of the socio-economic importance of the forestry and forest products industries.

6.3.2 General Sustainability Issues and Indicators

Considerable progress has been made over the past decade in understanding and measuring forest-related sustainability issues, although recent decades have also witnessed an increase in the scope and effectiveness of logging operations. In part, this work has been in response to Agenda 21's call for urgent action to conserve and sustain forest resources, given that many forests world wide are threatened by human activities (UNCED, 1992: Ch 11).

Sustainability issues

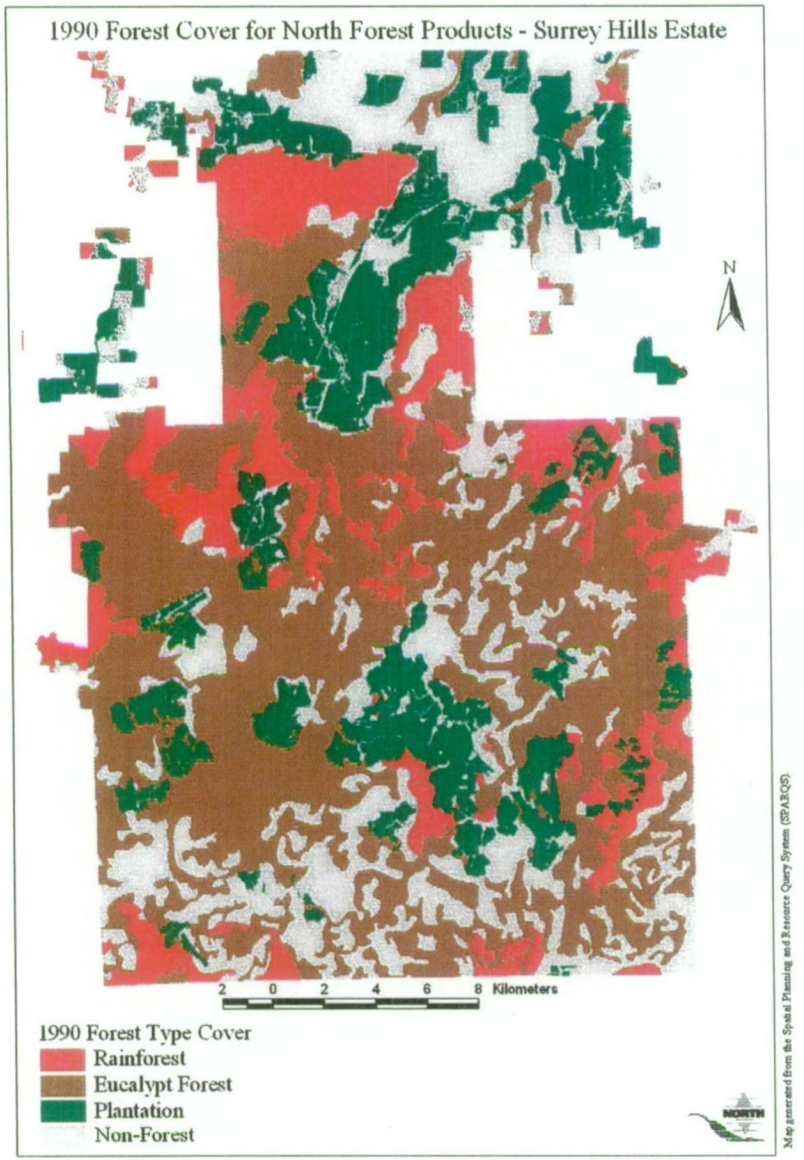
Timber harvesting and reforestation work is supported by a range of environment protection, biodiversity management, and socio-economic amenity practices. Timber harvesting is regulated by the *Forest Practices Act (1995),* and is carried out according to approved plans. The Act is supported by the *Forest Practices Code* (Forestry Commission, 1993).

Forestry impacts on biodiversity in many ways, and some impacts are difficult to avoid. In particular, the use of logging equipment and logging tracks facilitates the spread of weeds, feral animals, and pathogens. However, these problems can be mitigated (but not altogether prevented) by measures such as log track drainage provisions, requiring only fair-weather operations in areas sensitive to die-back fungus or soil erosion, and the use of wash-down stations. Fire management is another aspect of biodiversity conservation in forests. Low intensity burns are used to regenerate logged areas and to reduce fuel material, hence avoiding damaging high-intensity bushfires. Such burns were also carried out routinely by Aboriginals, and tended to result in a grassy, open forest undergrowth (Florence, 1994).

Fauna protection measures are described by the *Forest Practices Code,* Taylor (1991), and Jackson and Taylor (1994). Measures include protecting special habitats during logging operations, ensuring that a logged area is adjacent to similar forest so that wildlife can recolonise the area; and ensuring that plantation forests retain a mosaic of corridors that allow wildlife populations to interbreed, and maintain their genetic variation. Such corridors should be broad enough that fauna or flora populations are not subject to increased speciation and/or extinction pressures. Figure 6.6 shows the wildlife corridors planned by North Forest Burnie for their Surrey Hills property in north-west Tasmania.

The main physical environmental concerns are soil erosion and nutrient loss as a result of timber harvesting, and associated impacts on water quality and flow. Additional concerns include soil compaction, puddling, and mixing (Forestry Tasmania, 1997). Typical protection measures are to allow only limited tracks in logged areas; to reforest these areas quickly so that their vulnerability to soil erosion is minimised; to create streamside reserves; to put waterbars in tracks; and to leave natural debris on the ground to prevent soil erosion by water flow. The *Forest Practices Code* also provides guidance on the use of machinery, snig tracks, timber landings, logging practices in steep country, and so forth, while Brown and Laffan (1993) provide guidelines for the conservation and management of forest soils.

Forestry operations have several adverse socio-economic impacts. Landscape management measures include screening the visual impact of logged areas from road users (Forestry Commission, 1990), and the forest industry also educates people that logged areas do regenerate (to a large degree) over a period of years. Other mitigation measures include the provision of scenic forest reserves, with picnic areas, nature trails, and walking tracks (Forestry Tasmania, 1995). Individual wood processing facilities such as the Hampshire mill operate under approved environmental management plans (*e.g.* ETS 1993a, 1993b).



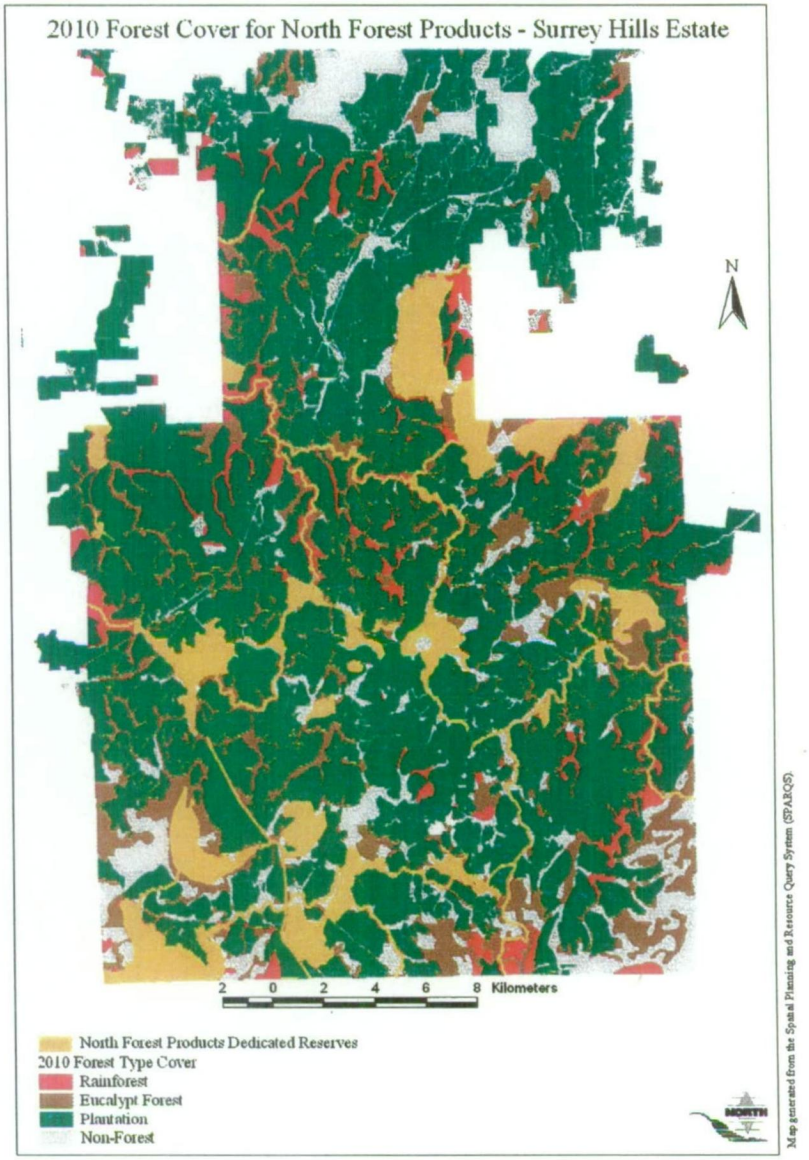


Figure 6.6 North Forest Surrey Hill Estate forest cover estimates for 1990 and 2010, showing wildlife corridors and streamside reserves.

Regional Forest Agreement

At a strategic level of resource management, the Tasmanian Regional Forest Agreement (RFA), was signed in late 1997 by the State and Commonwealth Governments. The RFA sets out a framework for the conservation, use and management of Tasmanian forests, based on forest and wilderness area reserve system criteria (ANZECC/MCFFA, 1997). The agreement provides resource security for the forest and forest products industries, while protecting forest conservation values, by aiming to preserve at least 15 % of the pre-1750 distribution of each forest ecosystem in the State, and 60 % of the remaining vulnerable forest ecosystems. Considerable effort is now being devoted to developing geographic information systems and databases to support forest management practices under the RFA.

Under the RFA, the State's forests are classified as follows (the percentages are preliminary estimates):

- *Multiple use forests*, which comprise about 30 % of Tasmanian forests, and are managed for both wood production and for conservation values. In north-west Tasmania, most multiple use forests are either on Crown land managed by Forestry Tasmania, or are on private land owned by North Forests Burnie.

- *Forest reserves*, which comprise about 38 % of Tasmanian forests, including some 60 % of the State's remaining rainforest.

- *Private forests*, which comprise about 32 % of Tasmanian forests.

Indicators

The Regional Forest Agreement specifies that sustainability indicators should be developed by late 1999, building on the Montreal Process Criteria for the sustainable management of temperate and boreal forests. These indicators are not yet available, but Table 6.6 proposes interim indicators. For the comparative sustainability assessments considered herein, it is sufficient to assign a single fingerprint indicator to each theme, and Table 6.7 shows the broad interpretation of extreme indictor values, using the usual 0-10 scale.

Considering biodiversity, habitat extent and quality are assumed to correlate to more fundamental quantities, such as genetic diversity, which are hard to measure directly. Our understanding of the biodiversity of NW Tasmania is incomplete, particularly quantitatively, and such understanding would need underpinning by comprehensive and systematic studies.

Theme/indicator	Primary considerations	
Biodiversity	***Habitat extent***	Total area of each native forest group.
	Habitat quality	Tree age and size distributions. Connectivity of habitats.
Socio-economic	***Employment***	Total direct forest industry employment. Total indirect forest industry employment.
	Value addition	Extent of timber product processing.
	Services	Education, health, recreation, shops.
	Community	Crime rate, community integrity indicators.
Physical environment	***Soil quality***	Soil quality in forested areas.
	Water quality	Water catchment well being.

Table 6.6 Sustainability indicators for forest industry operations.

Indicator	Bad (0-2)	Excellent (8-10)
Biodiversity	Clear-felled area.	Old growth native forest.
Socio-economic	Low employment & community integrity, poor education and health services, few amenities, high crime rate.	High employment & community integrity, good education and health services, good amenities, low crime rate.
Physical environment	Logged area with extensive soil erosion and heavy sedimentation of water courses.	National park, or similar area. Soil quality is high, and streams are pristine.

Table 6.7 Interpretation of extreme sustainability indicator values.

The main socio-economic indicators are direct and indirect employment, and value addition. Tasmanian forest product industries consist of log sawmilling, resawn and dressed timber producers, wood chip facilities, joinery and fabricated board manufacturers, furniture makers, and the paper, pulp & paperboard industries. Socio-economic services might include a semi-subjective measure of provision for recreation and tourism within forested areas. Tasmania's forests attracted about 400,000 visitors in 1997, and Forestry Tasmania (1995) describes forest reserve attractions for visitors. Other socio-economic factors that might be considered include wage income, the Tasmanian balance of trade, and tax revenue.

Considering the physical environment, most soils in Tasmanian forests have been mapped (Laffan and Neilsen, 1997), while water catchment management plans are being developed across Tasmania in accord with the *State Policy on Water Quality, 1997*. Soil quality

indicators are also being researched as part of a long term program of ecological research that comprises a suite of multi-disciplinary projects to better understand the ecological processes and biodiversity of a 16,000 ha forested site, known as the Warra, in southern Tasmania. The site contains both working forests and conservation reserves, and is mainly a tall wet eucalypt forest, the most common forest type in Tasmania.

The indicators set out in Table 6.6 can be consider as an extended version of the indicators that were used by the Resource Assessment Commission to evaluate scenarios of forest usage (RAC, 1992):

Economic indicators	***Environmental indicators***
Total value added	Remaining area of old-growth forest
Total direct employment	Area unavailable for logging
Balance of trade	Soil and water quality (subjective)

The Commission generated economic and environmental indices by assigning values to each of the indicators listed above, standardising these values to scores between 0 and 100, and then summing the scores. An Integrated Forest Model, INFORM, was then used to evaluate the scenarios of future forest usage (RAC, 1992).

6.3.3 Indicator Values

Table 6.8 sets out the estimated indicator values in the baseline year of 1990, together with estimated indicator values in the year 2010 for the planned forestry scenario. The rationale for assigning these values is discussed below.

	Biodiversity	***Socio-economic***	***Physical Env.***
1990 baseline	8 (Good/Excel.)	7 (Good)	9 (Excel.)
2010 planned forestry	7 (Good)	8 (Good/Excel.)	8 (Good/Excel.)

Table 6.8 Estimated indicators for 1990 and 2010 (planned forestry).

Biodiversity

The biodiversity indicator focuses on the forested areas of the Circular Head and Murchison forest districts, and the land associated with wood processing facilities within these districts. Table 6.9 shows forest zones in the Murchison and Circular Head forest districts (Forestry Tasmania, 1997; 1998a). The production zones include a number of special management zones for the conservation of intrinsic biodiversity and physical environmental values.

	Circular Head	Murchison	Both districts
Production zone	161,300	225,000	386,300
Conditional zone	12,900	1,000	13,900
Protection zone	33,400	48,000	81,400
	207,600	274,000	481,600

Table 6.9 Circular Head and Murchison districts State forest zone areas (ha), 1998.

Forestry Tasmania (1998b) sets out the wood harvesting plans for these forest districts for the period 1998/99 to 2000/01. The total area to be logged in the two forest districts over this three year period is 6,326 ha, of which 4,192 ha will be converted to plantation forest, and the remainder will be returned to native forest. The forest cover statistics for North Forest Products's Surrey Hills estate from 1990 to 2010 are shown in Table 6.10.

	1990	2010
Eucalypt forest	46,454	23,454
Rainforest	11,599	5,603
Plantations	20,464	61,935

Table 6.10 North Forest Products Surrey Hills estate forest cover (ha)

If the three-year rate and pattern of timber harvesting from State forests is applied over a 20 year period, and the timber harvesting from North Forest Products is also considered, then some 69,418 ha of native forest will be converted to plantation forest, and 14,427 ha will be returned to native forest. The total area of forest involved is 83,845 ha, about 17.5 % of the forested area of the two forest districts. If allowance is made for timber harvesting operations in private forests, then about 20% of the districts will be logged over a 20 year period.

In assigning a biodiversity indicator value of 7 (good) in 2010 for the planned forestry scenario, it was noted that while plantation forests have less biodiversity than native forests, they are far from devoid of life. Suckling et al. (1976) found 11 native fauna species in a Victorian pine plantation, compared to 14 in a nearby mature eucalypt forest.

Under a frontier economics scenario, it is assumed that logging is unguided by the *Forest Practices Code*. Both forestry and wood processing facilities operate with no consideration of biodiversity conservation, or physical environment protection. Logged land would be either converted to other uses, or left to regenerate without assistance.

Socio-economic

The socio-economic indicator is related to the north-west Tasmanian municipalities that comprise the two forest districts. Madden and Hagger (1991) estimated that the forestry and forest products industry contributed about 20,500 jobs to the Tasmanian economy in 1985-86, about 11.9 % of the total employment for that year. Roughly one-third of this activity relates to north-west Tasmania. Madden and Pant (1997) carried out a study that further highlighted the importance of these industries to the Tasmanian economy.

The early 1990s saw a significant expansion in wood chipping activities, and most wood chips are currently exported to Japan. Felmingham (1995) and TS&F (1994) have concluded that these exports have significant economic benefits. In the 20 year time frame considered by this case study, the resource security provided by the Regional Forests Agreement is expected to encourage the establishment of domestic pulpwood facilities. The socio-economic indicator relates to the overall economies of the municipalities within the two forest districts, and the indicator value for the planned forestry scenario is expected to improve slightly from 7 (good) in 1990 to 8 (good/excellent) in 2010.

Physical environment

The physical environment indicator relates to the same geographic area as the biodiversity indicator, and the two indicators have similar values. However, the biodiversity of the forest districts has been impacted slightly more by the development of Tasmania through to the baseline year of 1990. Soil surveys have found that the Circular Head and Murchison forest districts contain soil types which range from high quality red basalt soils to far lower quality soils (Laffan and Neilsen, 1997; Grant et al., 1995). Overall, based on discussions with Forestry Tasmania (Mr Mike Laffan, October 1998), it is judged that the forested areas in the two forest districts in 1990 were characterised by a high soil and water quality. Under the planned forestry scenario, the physical environment indicator value is expected to decrease slightly, from 9 (excellent) to 8 (good/excellent).

6.3.4 Indicator Interactions

Table 6.11 summarises the dominant indicator interactions, their estimated e-folding response times, and the rule group weights. The interactions were identified with the assistance of Mr Malcolm Hatcher, North Forest Burnie's environmental manager; and through discussions with Forestry Tasmania staff, and several site visits in 1998.

Both the case studies presented in this chapter consider the broad interactions of the three sustainability themes over large areas. The two indicator interaction patterns are the same, the interaction weights are very similar, and no justification is perceived in either case study for weighting the new indicator changes calculated by each iteration.

	Biodiversity	**Socio-economic**	**Physical environment**
$(\Delta Bio)^{old}$	**Positive: Weight = 1.** 4 years. Improved reforestation will allow recolonisation by fauna & flora.	**Positive: Weight = 1.** 4 years. Improved biodiversity increases recreational & tourist potential.	**Positive: Weight = 1** 4 years. Improved reforestation reduces soil erosion.
$(\Delta Soc)^{old}$	**Negative: Weight = 1.** 2 years. More wood harvesting & processing facilities leads to loss of habitat extent and quality.	**Positive: Weight = 4.** 2 years. Improves forest industry leads to support business opportunities, and better schools etc.	**Negative: Weight = 1** 2 years. More wood harvesting & processing facilities leads to degraded soil and water quality.
$(\Delta Env)^{old}$	**Positive: Weight = 3.** 2 years. Degradation of soil and water quality adversely impacts dependent ecosystems.	**Positive: Weight = 1.** 4 years. Better environmental quality improves timber resource, and tourist & recreational potential.	**Positive: Weight = 1.** 2 years. Soil erosion leads to sedimentation in streams.
	$(\Delta Bio)^{new}$	$(\Delta Soc)^{new}$	$(\Delta Env)^{new}$

Table 6.11 Indicator interactions, estimated e-folding times, and rule group weights.

Considering the interaction processes identified in Table 6.11, an assessment on the scale of two forest districts assumes that impacts can be mitigated, but not avoided. For example, in the $\Delta Soc^{old} \rightarrow \Delta Env^{new}$ interaction, an increase in the employment and value addition socio-economic indicators reflects an increase in forestry and forest product operations. The nature of logging equipment and infrastructure, and of wood processing facilities, is such that they tend to reduce soil and water quality, no matter how good the impact mitigation measures. There may be other interactions, including some positive interactions, but this is judged to be the dominant mechanism.

As for the Mount Lyell case study, the system of indicators will have an overall e-folding time which is similar to the slowest interactions (4 years), achieving 95 % of a new equilibrium some 12 years (three e-folding times) after the cessation of model forcing, with

each iteration corresponding to about 20 months. Again, this is only a rough calculation, but it is sufficient to allow the comparative sustainability assessments presented herein.

6.3.5 Model Forcing

Table 6.12 sets out the indicator changes used to drive each assessment. The rationale for the specified changes is set out below. Additional advice on the forcing changes was provided by Mr Malcolm Hatcher, North Forest Burnie's environmental manager, Mr Mike Laffan, a soil specialist with Forestry Tasmania, and a local economist familiar with the forestry industry (name withheld by request).

	Biodiversity	*Socio-economic*	*Physical Env.*
Planned forestry	-0.1	+0.3	-0.1
Frontier economics	-0.3	+0.4	-0.3
	Changes for initial step and after each of the first five iterations.		
Deep ecology	+1.0	-1.5	+0.25
	Changes specified for the initial step only.		

Table 6.12 Indicator changes specified to drive the model.

Planned forestry operations involve ongoing timber harvesting and processing, so that model forcing is best applied by specifying both initial indicator changes, and additional indicator changes at the end of each iteration. The initial time step is taken to be a 20 month period, the same as the period associated with each iteration, and specification of indicator changes over this period takes into account that the period is associated with the slowest interactions.

The specified biodiversity and physical environmental indicator changes are negative, and relatively small (each is -0.1), given the impact mitigation measures outlined above. The socio-economic indicator change is positive and slightly larger (+0.3), reflecting the investment and employment generated by the increase in woodchip export quotas, and the resource security provided by the Regional Forests Agreement. In this exercise, the sizes of additional indicator changes are assumed to be constant, and to stop after a nominal 10 year period (six 20 month time steps). After this time, the indicator interactions play themselves out over a further 6 or 7 iterations (*i.e.* 10 or so years), bringing the scenario to 2010. A more detailed approach to model forcing would reduce the sizes of the additional indicator changes with each iteration, commensurate with the absolute indicator values.

The same model forcing approach is used for the frontier economics scenario. The specified biodiversity and physical environmental indicator changes are negative, and larger than for

the planned forestry scenario (each is -0.3). The socio-economic indicator change is positive, and slightly larger than for the planned forestry scenario (+0.4), assuming that (in the short term) exploitation of the resource more than compensates for any adverse impacts due to the loss of eco-tourism and the natural resource base. For comparison to the planned forestry scenario, the sizes of additional indicator changes are again assumed to be constant, and to stop after a nominal 10 year period.

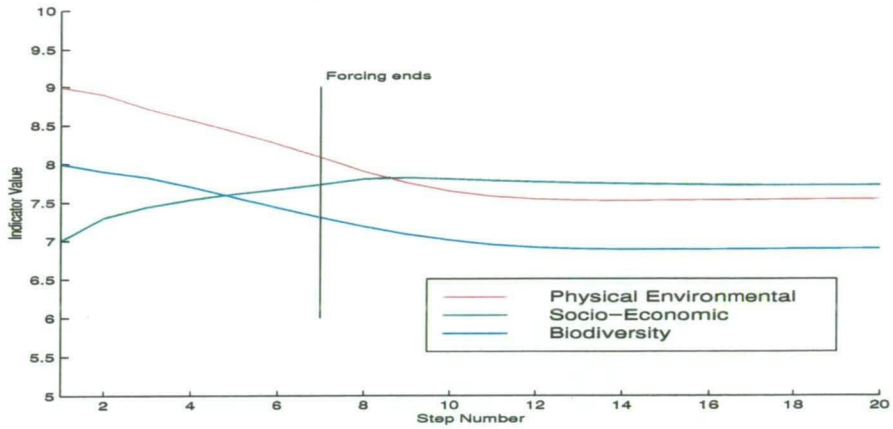
The deep ecology assessment is driven by an impulse, with a set of initial indicator changes specified that correspond to the close-down of the forestry and forest product industries, and the establishment of national parks. The biodiversity and physical environmental indicators are positive, but only small since the baseline indicator values are already in the *good* to *excellent* range. The socio-economic indicator change is negative and larger, reflecting the impact which removal of the forestry and timber processing industries would have on the region. The initial indicator changes are assumed to occur over a nominal period of 1-2 years, following which the indicator interactions play themselves out.

6.3.6 Model Predictions

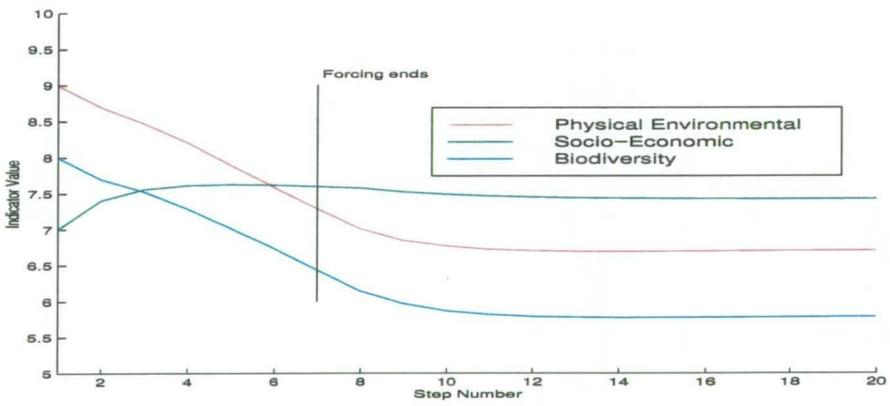
Figure 6.7 and Table 6.11 present the model predictions. The planned forestry scenario slightly improves the regional socio-economy over the 20 year period to 2010, and slightly decreases the biodiversity and physical environmental quality. The model predictions agree well with the estimated indicator values.

The frontier economics scenario is a disaster. The low physical environment and biodiversity indicators reflect the fact that some 20 percent of the forested area of the two forest districts has been logged out, with little regeneration and significant environmental degradation. The socio-economic indicator rises during the period of forcing, but falls slightly once forcing ceases and the indicator interactions play themselves out. It is interesting to note that the socio-economic indicator is predicted to be slightly less under a frontier economics scenario than under the planned forestry scenario, even though the indicator is driven for the first ten years (7 time steps) by slightly larger positive changes (+0.4 compared to +0.3).

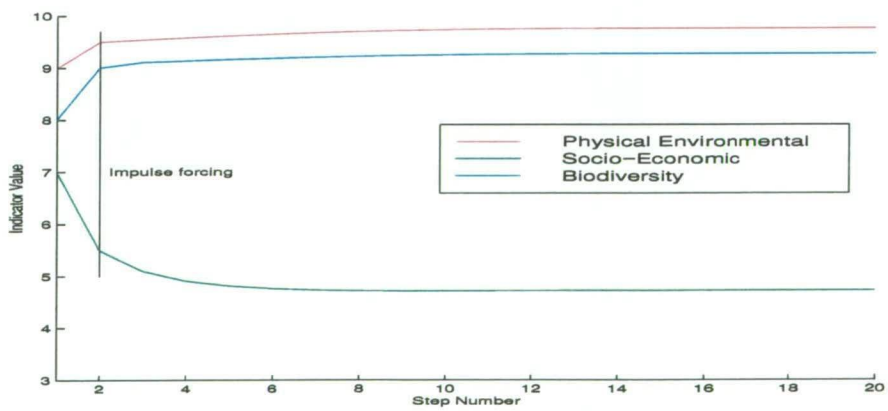
In the deep ecology scenario, the physical environmental quality and biodiversity are slightly improved, but cannot improve much since they were already good/excellent. However, the socio-economic indicator is substantially reduced, since increased eco-tourism cannot compensate for the loss of the forestry and timber processing products industries.



Planned forestry operations.



Frontier economics scenario.



Deep ecology scenario.

Figure 6.7 Model predictions.

Theme / indicator	1990	2010. Planned Forestry		Frontier Economics	Deep Ecology
		Expected	*Model*		
Biodiversity	8 Good/Excel.	7 Good	6.9 Good	5.8 Okay	9.3 Excellent
Socio-economic	7 Good	8 Good/Excel.	7.7 Good	7.4 Good	4.7 Poor
Physical environmental	9 Excellent	8 Good/Excel.	7.6 Good	6.7 Okay	9.8 Excellent

Table 6.11 Expected vs. predicted sustainability indicator values.

6.4 Discussion

The two case studies presented in this chapter have illustrated the use of the sustainability assessment method as a straightforward tool for examining the basic impact of projects. The method is more than just the fuzzy rule model used to predict indicator changes. The case studies demonstrate the systematic examination of sustainability issues, indicators and their interactions, and this process is itself a major step forward from the present situation. Too many planning decisions appear to be driven by "here-and-now" considerations, in spite of the agreed need for sustainable planning.

As noted in Chapter 5, regional indicator data of sufficient quality to properly test the fuzzy rule model do not yet exist. In both case studies, each sustainability theme was described by a single fingerprint indicator; and the estimation of baseline indicator values, and indicator interactions relied to a large extent on professional judgement. Furthermore, fairly crude forcing was used to drive the indicator change prediction model. Nevertheless, the model predictions based on these assumptions were believable, and provided clear conclusions regarding the sustainability impact of different project options. In other words, the assessment method is particularly useful when used as a comparative tool. In the Mount Lyell case study, the continuation of the mine is clearly better than the mine closure scenario; and the relative merits of the three forestry scenarios were also clear.

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7.0 TRANSPORT PLANNING CASE STUDY

7.1 Introduction: The Western Explorer

Figure 7.1 shows the Western Explorer road in north-west Tasmania, which links the sealed road between Smithton and Arthur River in the Circular Head municipality, to the mainly sealed road between Corinna and Zeehan in the West Coast municipality. The Arthur River is bridged, while Corinna is a small-vehicle ferry crossing station on the Pieman River.

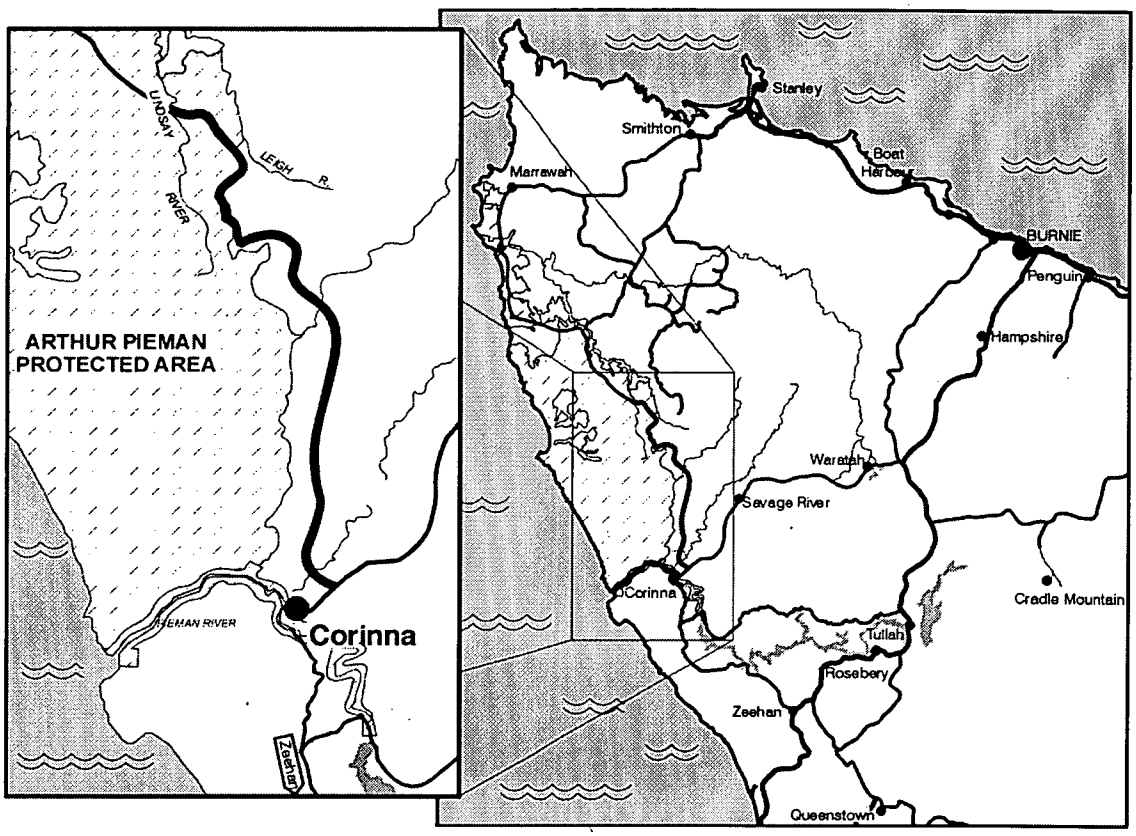


Figure 7.1 The Western Explorer in NW Tasmania (courtesy Dept. of Transport). The exploded area is about 30 km x 55 km.

The Western Explorer between Arthur River and Corinna was constructed in two phases. The road south to the Lindsay River was completed in 1987, and the link road to Corinna was completed in 1995/96. The link road project was supported by a Development Proposal and Environmental Management Plan, which justifies the completion of the Western Explorer as beneficial to both tourists and the local community, noting that it will permit easier access to bushwalking trails and river rafting (Thompson & Brett, 1993).

The present road is unsealed, except for short stretches, and has a design speed of 50 km/h. Suggestions have been made that the road be upgraded, and the assessments presented

herein examine both the sustainability impact of completing the final link of the Western Explorer, and the consequences of a decision to upgrade the road.

1. Present situation. This exercise assesses the sustainability impact of completing the Western Explorer road. The assessment baseline year is 1993, just prior to construction of the link section between the Lindsay River and Corinna. The geographic area is the transport corridor between Smithton and Zeehan.

2. Road upgrade. These exercises assess the sustainability impact of upgrading the Western Explorer road by sealing it, widening it in places, and improving its vertical and horizontal alignments. The geographic area is as for the first assessment.

a) Strong planning scenario. This scenario assumes that follow-on developments in the Circular Head Municipality are subject to stringent planning controls, and that only off-road activities compatible with wilderness areas are allowed within the Arthur-Pieman region of the transport corridor. The planning constraints for this region would thus be similar to those that pertain to the section of the Lyell Highway that passes through World Heritage wilderness areas, in west Tasmania.

b) Weak planning scenario. This scenario assumes that any developments or off-road activities that may be triggered by an upgrade to the Western Explorer are largely uncontrolled. This scenario can be compared to the evolution of the transport corridor between Hobart and Launceston, discussed in Section 7.2.3.

7.2 Sustainability Issues and Indicators

7.2.1 Non-Urban Transport

Almost all of Tasmania's 3,500 km of state-owned roads are non-urban in nature, and most road projects can be categorised as construction or upgrade projects, community by-passes, or transport corridor management projects. The need to integrate land use and transport planning is difficult to translate into practice because of the traditional view that transport should support rather than control development, and because many planning schemes have not yet been updated to accord with modern resource management philosophies (Chapter 2). In 1996, the Tasmanian government developed a draft sustainable development policy on

roads, but it was withdrawn due to disagreement on how to approach the various issues (SDAC, 1996; Carter, 1996).

Table 7.1 proposes indicator areas which describe the sustainability issues associated with most non-urban road projects. The indicator areas are consistent with those suggested for State of the Environment reporting (Carter, 1999; Houghton, 1998; Carter and Pauley, 1996). As this case study will demonstrate, significant insight can be gained into the sustainability impact of a project by using only a single fingerprint indicator of each sustainability theme, based on consideration of the component factors.

	Indicator areas	
Biodiversity	***Habitat & flora***	Habitat extent, integrity and quality. Number, distribution and conservation status of flora species.
	Fauna	Number, distribution and conservation status of fauna species.
Socio-economic	***Road users***	Major communities linked by a road; and road users travelling between these communities, including tourists and freight carriers. People living in communities within the transport corridor who depend on road users for their business.
	Local people	Local communities within the transport corridor, especially people who do not depend on road users for their business. Aboriginal people with heritage links to the region.
Physical Environment	***Soil quality***	Usually within the transport corridor.
	Water quality	In adjacent streams, lakes, wetlands etc.
	Air quality	Both local pollution and greenhouse gas emissions.

Table 7.1 Sustainability indicators for non-urban road projects.

Biodiversity issues are very important for non-urban road projects. The protection of remnant vegetation in transport corridor management projects, and revegetation following civil works, are particular problem areas (Carter, 1997; Farmer-Bowers and Ward, 1995).

Considering the physical environment, road construction or upgrade projects can threaten soil and water course quality through a number of mechanisms, most of which can be substantially mitigated. In the longer term, service stations, vehicle emissions and spillages, and even road construction materials, are all threats to soil and water quality. Local air quality is less of a concern than for urban road transport.

It is convenient to divide the socio-economic issues and indicators into those associated with *Road Users*, and those associated with *Local People*, since these two groups usually have

different viewpoints and interests. *Road Users* are defined as the primary users of a road, including tourists; the communities linked by the road; and people living within the transport corridor who depend on road users for business. *Local People* are defined as people such as farmers who live within the transport corridor, but who do not consider either the road or its users to be of prime importance for their business. Aboriginal people who have heritage ("spiritual") links with land in the environs of a transport corridor also fit the definition of Local People, even though they may not currently live in the area. It is important to consider such links when assessing the impact of a project, although it is difficult to quantify such links. However, the sustainability assessment method is perhaps most effective when it used to compare project options, and for such applications relative strengths can be assigned to the Local People indicator.

From a planning perspective, it is important to distinguish between intrinsic and follow-on sustainability issues. Table 7.2 gives examples of intrinsic issues, which are those issues that are unavoidably associated with a project, although the severity of impacts may be mitigated (Carter, 1997). Follow-on issues are those which can be either encouraged or suppressed by planning decisions, and typically involve land use changes enabled by the road. For example, the 1970 upgrade of Hobart's southern outlet road was followed by the rapid development of Kingston and Blackmans Bay as commuter communities (SDAC, 1996). However, while the road upgrade was a necessary precursor to development activity, planning authorities could have prevented the development had they wished to do so.

7.2.2 General Transport Issues

To place the sustainability issues associated with non-urban road projects in to perspective, it is worth briefly reviewing the broader context. The sustainability impacts of urban road traffic and infrastructure range from the obvious problems of traffic congestion, noise, vehicle emissions, road safety, through to more strategic concerns such as minimising threats to community integrity (Austroads 1994, 1995, 1997a; and ABS, 1997). The construction and operation of roads and vehicles consumes resources and energy, including large quantities of fossil fuels. The transport industry also produces a substantial waste stream, which includes vehicle bodies, old tires, old batteries, and waste motor oils.

In an urban context, transport planning policies tend to focus on socio-economic issues, and their main goal is to promote the safe and rapid movement of people and freight, while minimising traffic congestion and nuisance to urban communities. In the United Kingdom, for example, there is an awareness that the establishment of urban villages can reduce the

Biodiversity	**Socio-economic**	**Physical environmental**
Roads attract wildlife in a number of ways, and can act as traps for animals, especially at night. Road kills often involve healthy animals, not just the very young, sick, or old. Predators such as kookaburras learn that prey animals are exposed when they cross roads. Secondary road kills are a major problem. Road upgrades have been known to decimate some animal populations (*e.g.* NSW EPA, 1993).	Road transport provides essential support to many communities, but can also threaten community integrity. Performance indicators include freight transport statistics, vehicle kms travelled, travel time, smooth travel exposure (*i.e.* road condition), and construction expenditure return (Austroads, 1996; 1997a; and 1997b).	Vehicle emissions degrade local air quality, although this is primarily an urban problem. Vehicle emissions contribute significantly to global warming. Tasmania has a relative old vehicle fleet, which exacerbates the problem.
Transport corridors facilitate the spread of weeds such as ragwort, feral animals, and pathogens such as die-back fungi.	Road safety. Austroads (1997b) provides several indicators of road safety. In Tasmania, the majority of fatal accidents occur on rural roads.	Soil and groundwater quality are put at risk by road construction materials, lead in vehicle emissions, service station operations (notably underground fuel tanks), and accidental spillages.
Native vegetation. Road reserves are the last bastions of remnant vegetation in some areas.	Noise and vibration nuisance from vehicles is usually associated with urban traffic, but many dwellings in Tasmania are located in close proximity to State roads.	Road works can lead to soil erosion and sedimentation of waterways, particularly when revegetation is a problem. Increased sediment load can stress aquatic ecosystems.
Roads reduce and fragment habitat, and are barriers across wildlife corridors. Populations of flora and fauna become isolated and confined to smaller areas, with associated reduction in genetic variation and viability of species (the 'island' effect).	European and Aboriginal heritage features can be impacted by road projects. It is worth noting that Aboriginal land usages are not necessarily congruent with the goals of the conservation movement.	Roads channel stormwater run-off, and can influence local drainage patterns. Stormwater is typically polluted by a range of contaminants, which degrade receiving water quality.
	Roads, and waste dumped on roadsides, adversely impact on landscape aesthetics.	Spillage, and waste dumped on roadsides, adversely impact on environmental quality.

Table 7.2 Sustainability issues intrinsically associated with non-urban road projects.

need to travel (HMSO, 1995). The main physical environmental concerns are air quality, stormwater runoff, and greenhouse gas emissions. Biodiversity issues usually play a secondary role in the sustainability vision for a city.

Considering Australian cities, the national ecologically sustainable development strategy process was supported by a working group on transport (ESDWG, 1991; ESDSC, 1992). More recently, the Better Cities Program and Australia's Land Transport Strategy have helped to improve public transport systems, reduce traffic congestion and transport-related pollution, and prevent urban sprawl (DTC, 1993).

7.2.3 The Hobart-Launceston Transport Corridor

One assessment scenario examines an upgrade of the Western Explorer when subsequent development and activities in the Arthur-Pieman region of the transport corridor are essentially uncontrolled, or at least very pro-development. Insight into the likely evolution of the Western Explorer transport corridor under these conditions can be gained by considering the history of the 200 km transport corridor linking Hobart and Launceston, Tasmania's principal urban centers.

Tasmania was colonised in 1804, and Newitt (1988) reviews the history of the early road linking the pioneer towns of Hobart and Launceston, and the small communities which were established along the road, such as Kempton and Ross, located about a day's horse ride (say, 20 km) apart from each other. Prior to the 1800s, the region was characterised by a physical environment of excellent quality. The region's biodiversity had been substantially influenced by Aboriginal land management practices, such as the use of low temperature fire to reduce forest and woodland floor fuel loads. Nevertheless, the area was still characterised by biodiversity which included grassy plains, bush and woodland communities, and large fauna such as emus, Tasmanian tigers, and wombats.

The development of the transport corridor has not significantly impacted the physical environment of the region, except for localised problems of soil erosion due to land clearance, or transport-related soil contamination (*e.g.* from service stations). In contrast, the region's biodiversity has greatly changed over the years, and today it has a much diminished biodiversity compared to the early 1800s. Many remaining trees are suffering from die-back, as shown in Figure 7.2 (Forestry Commission, 1991; Neyland, 1996). Figure 7.3 shows that land alienation in the vicinity of the transport corridor occurred rapidly, the principal motivation being to clear land for stock grazing and agriculture (Scott, 1965).

Figure 7.2 Eucalypt die-back and lack of tree regeneration near Oatlands (view from the highway, about halfway between Hobart and Launceston).

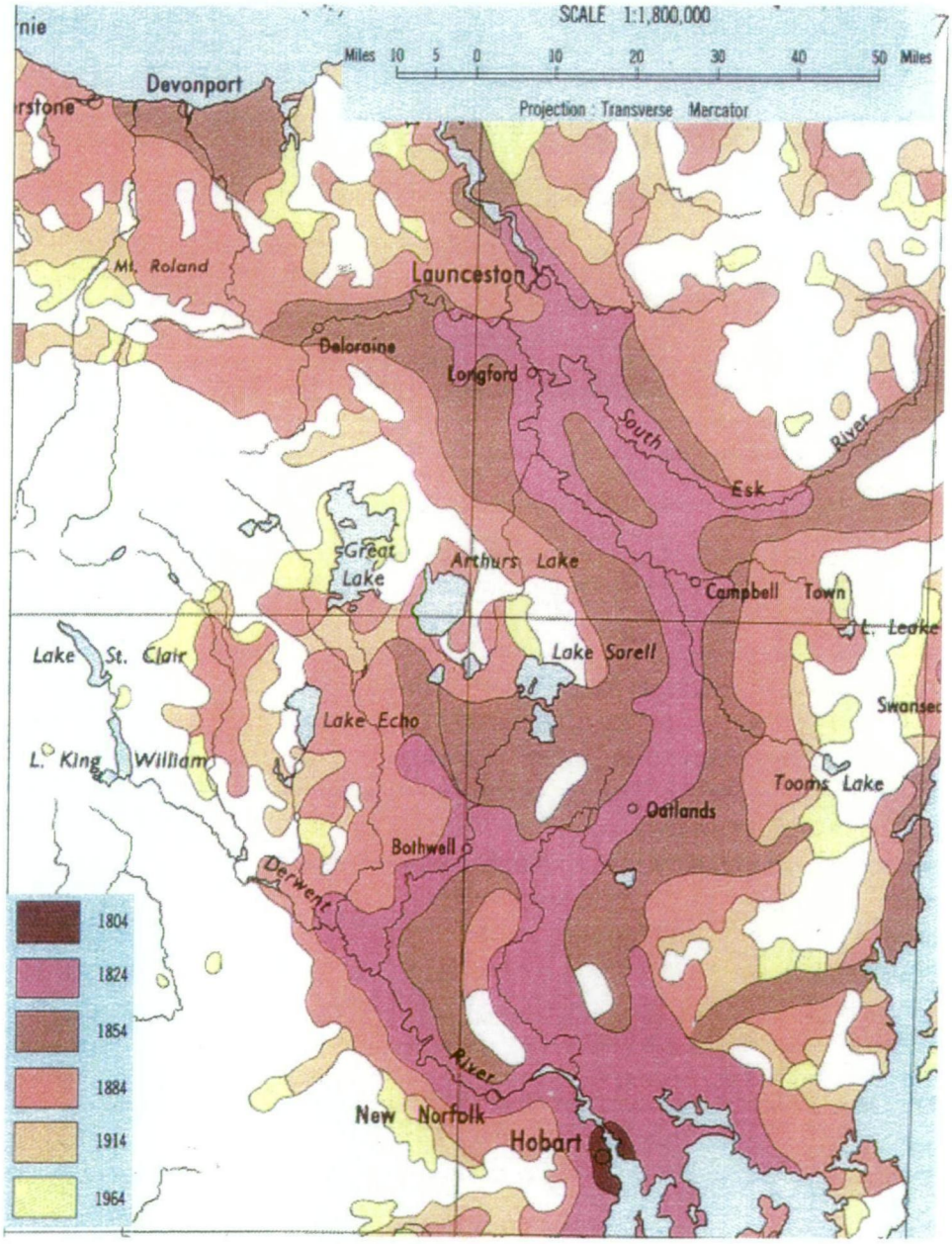


Figure 7.3 Land clearance in the Tasmanian midlands (after Scott, 1965).

Another threat to regional biodiversity has been the steady increase in road traffic volume and speeds, and the increase in night-time travel (many marsupials being nocturnal). As vehicle technology has improved and road usage has grown, the road has become more of a barrier to wildlife corridors, and road kills have increased.

The socio-economic aspects of both the Road Users and the Local People have also changed over the years. In the 1800s, communities within the transport corridor provided travellers with accommodation and supplies, while the road enabled the transport of agricultural and pastoral produce to the markets of Hobart and Launceston. Horses and carriages gave way to motor vehicles in the early 1900s, and travellers could make a one-way journey between Hobart and Launceston in a single day. Inter-city trade grew, and the communities within the transport corridor also grew as they became rural centers. Stancombe (1968) details many of these changes in his history of the road in the 1900s. Road user support services changed to keep pace with technology, with vehicle maintenance and refuelling services replacing horse stabling facilities, and cafés replacing guest houses.

It became routine in the 1950s for travellers to make the return trip between Hobart and Launceston in a single day, and road traffic began to include a significant number of vehicles, including freight vehicles, travelling to and from Tasmania's north coast port communities. Further upgrades in the 1990s have enabled B-double freight transport ("road trains") to use the highway. As early as the 1970s, communities within the transport corridor began to experience road safety and traffic nuisance concerns. Consequently, when the road was upgraded in the 1970s and 1980s to become part of the national highway network (the Midlands Highway), several community by-passes were engineered. Some communities, such as Ross and Oatlands, have survived as rural centers, and their historic nature has attracted tourists. Others, such as Jordan and Epping Forest, have diminished.

7.3 Project Issues and Indicator Values

7.3.1 Summary of Indicator Values

For the purpose of the comparative assessments considered herein, the sustainability themes are described by three fingerprint indicators. The *Road User* and *Local People* socio-economic indicators are as outlined above. The *Environment* indicator comprises both the biodiversity and physical environmental characteristics of the region through which the new transport corridor passes.

Table 7.3 sets out the estimated fingerprint indicator values in 1993 and 1998, using the usual 0-10 scale. The values are based on the literature review summarised below, and on a site visit by the author and Mr Gillian of the State Department of Transport. Ms Cathy Searle, who carried out the archaeological surveys reported in Thompson and Brett (1993), provided advice regarding appropriate Local People indicator values.

	Environment	***Road Users***	***Local People***
1993	9.0 (Excellent)	4.0 (Poor/Okay)	7.0 (Good)
1998	8.5 (Good/excellent)	6.5 (Good)	6.0 (Okay/Good)

Table 7.3 Estimated indicator values (0-10 scale) in 1993 and 1998.

In 1993, the biodiversity and physical environment characteristics were slightly degraded with respect to wilderness quality, but were still excellent. The Road Users group was poor/okay, with some tourists and people in road head communities benefiting from the Western Explorer before completion. The Local People group condition was good, with farmers, abalone divers, and other enjoying a good quality of life, while the Aboriginal community had quite strong ties to the region.

By 1998, some 3 to 4 years after construction of the link road, the environmental quality had diminished slightly, with some signs of die-back, habitat damage and soil/water quality degradation in the vicinity of road, but no significant additional impact from off-road recreational activities. The Road Users group had benefited slightly from completion of the link road, with 15- 20 vehicles per day using the Western Explorer, and an associated increase in business for the tourist industry. The Local People group is judged to overall have been slightly adversely impacted, mainly because Aboriginal cultural values have slightly diminished, with minor negative impacts such as road safety concerns.

7.3.2 The 1993 Situation

Road Users

The Road Users group for the Western Explorer project consists of people using the road either as tourists, or to access off-road recreational activities such as bushwalks, river rafting or 4WD tours; and people who service the tourist industry. These people live mainly in the Circular Head municipality or in the transport corridor. West Coast municipality residents,

including those living in Zeehan, are not significantly impacted by the Western Explorer. There are no other road users, since trade between communities in the Circular Head and the West Coast municipalities relies on the Murchison Highway, not the Western Explorer.

In 1993, the north coast towns of Stanley and Smithton recorded some 77,000 and 47,000 visitors respectively, compared to roughly 100,000 visitors to Zeehan and Strahan at the south end of the Western Explorer (Tourism Tasmania, 1997). The Tall Timbers hotel in Smithton is estimated to have hosted coaches on about 220 nights in 1993 from interstate tour operators. Within the transport corridor of the incomplete Western Explorer, local eco-tourism businesses included the Arthur River and Pieman river cruise operators, and 4WD tours operated from the Blue Wren café at Marrawah.

Local People

The Local People group for the Western Explorer project is defined as people associated with the region through which the transport corridor passes, but who do not service the tourist industry. These people include farmers and graziers, and there are also several shacks on the coast south of Arthur River, most belonging to abalone divers. The region, particularly near the coast, was well populated by Aboriginal people prior to Europeans arriving in Tasmania, and the Aboriginal community feels strong heritage links to the region, although very few indigenous people live in the area at present. The high density of Aboriginal sites provides an invaluable archaeological record of the activities of the north west Aborigines, and all such sites are protected by the *Historic Cultural Heritage Act (1995),* and its 1997 amendments (Harries, 1992; and the archaeology report by C. Searle in Thompson & Brett, 1993).

Environment (Biodiversity and the Physical Environment)

The diverse natural resources of the region are comprehensively reviewed by Harries (1992), and several environmental reports are included in Thompson & Brett (1993). At first pass, the region's biodiversity and physical environment appear to be near wilderness. However, the region had been significantly influenced by the Aboriginal people who occupied the region prior to the arrival of European settlers in the 1800s, and has subsequently been extensively prospected and occasionally mined for minerals. Nevertheless, the region's physical environment is mostly high quality, and contains biodiversity that for the most part has not been exposed to the impact of European colonisation.

A 3,500 km^2 portion of the area has been named the Tarkine by conservation groups, after one of the bands within the north-west Aboriginal community, and the Western Explorer transport corridor passes through this area. Further information on the Tarkine is provided by TWS (1995); and in a World Heritage Nomination for the Tarkine, prepared by the Tasmanian Wilderness Society (TWS, 1992): the nomination has not been advanced.

The southern part of the transport corridor passes by and through a large tract of temperate rainforest on the Savage River plateau and its surrounds. This rainforest has high conservation significance (Harries, 1992), and is a deferred forest under the Regional Forest Agreement. The environs of northern part of the Western Explorer is characterised by buttongrass plant communities and scrub vegetation. The zoological studies presented in Harries (1992) concluded that the region contains a wide diversity of vertebrate and invertebrate fauna that has suffered minimal invasion by introduced predators.

7.3.3 The 1998 Situation

On 22-24 July 1998, the author and Mr Jed Gillian of the State Department of Transport travelled the Western Explorer road, and discussed the road's condition, usage and impacts with people in the Circular Head and West Coast municipalities, including representatives of the Circular Head Council. Mr Gillian is a senior environmental planner who was involved with the Western Explorer's route selection and road design.

Road Users and Local People

Vehicle monitoring by the Department of Transport, and Corinna ferry records, indicate that some 16 vehicles per day use the road, on average. This limited usage is partly because few rental car agencies insure their vehicles for travel on unsealed roads, and because few coach operators will risk travel on the present road. The Tall Timbers hotel in Smithton reports that completion of the Western Explorer has made little difference to tourists visiting the region by coach , although one tour operator plans a single coach trip per month in 1999, and these tourists will also take the Pieman river cruise.

Completion of the Western Explorer has thus had only a small overall impact on the local tourist industry. The Corinna ferry operator has been the major beneficiary, and there has been some development in the communities of Arthur River, Marrawa and Edith Creek, with a Circular Head council officer reporting that about six holiday shack and caravan developments have been approved over the last four years, together with a new shop and petrol station (Mr Mark Goldstone, Manager of Development Services, pers. comm.).

Environment (Biodiversity and the Physical Environment)

The Western Explorer has slightly impacted the physical environmental quality in the vicinity of the road. Some road sections are suffering from drainage problems, with a few drainage controls completely blocked by sediment. The gravel surface is degraded and slippery in places, through washing out of the fines (see Figure 7.4).

Figure 7.4 Roadside drainage problems.

The main biodiversity concerns are the facilitated spread of weeds and feral animals. The spread of pathogens is also a concern, but patches of die back fungus are already established in the area (Mr Andrew North's biology report in Thompson and Brett, 1993). Road kills are not an issue, since road travel is essentially confined to daylight hours (the ferry at Corinna only operates during daylight hours), and since the design speed of the road is only 50 km/h. The final link road section has been rehabilitated fairly well, with peat and topsoil replaced on top of the roadside construction zone, but earlier sections of the roadside in the north part of the road, near Arthur River, have not yet recovered.

Off-road activities such as river rafting and 4WD usage appear to have been very limited to date, and the site visit found little evidence of any impact from such activitiesd. There has been an increase in the frequency of Arthur River and Pieman River cruises, but these businesses are closely monitored by environmental authorities, and any impact from their operations (*e.g.* bank erosion from boat wash) has been minor. The State Government is currently examining the shacks south of Arthur River under the *Crown Land (Shack Sites) Bill 1997*, to ensure that they have minimal environmental impact.

7.3.4 Road Upgrade Issues

The pattern of Tasmanian visitor statistics set out in Tourism Tasmania (1997) suggests that sealing the Western Explorer might generate an additional 50,000 visitors per year to the Circular Head municipality, since coaches could continue from Smithton through to the West Coast municipality without backtracking.

Conservation group concerns about the Western Explorer project focused on follow-on sustainability issues, notably the fear that road completion would lead to rainforest logging and mining. However, the forestry and mining industries can rapidly engineer their own access roads to any areas which are approved for logging or mining. Follow-on issues which depend more heavily on the existence of the road are the incremental development of communities such as Arthur River, together with uncontrolled shack construction and off-road recreational activities, which would degrade the near wilderness quality of the region (Hughes, 1995; Konkes 1996; TWS, 1995).

In the strong planning scenario, the impact of these activities is assumed to be mitigated through provision of designated bushwalks, toilets, and scenic viewpoints; and through control of 4WD tracks, promotion of the 4WD Code of Practice, and provision of wheel-wash stations. However, it is difficult to mitigate some intrinsic issues, such as road kills (although Bauer (1998) reports that the Department of Transport has had some success in this endeavour).

As noted in Chapter 6, the future of the rainforest will be determined by the Regional Forests Agreement process, while the Arthur Pieman Conservation committee is the body charged with putting together a management plan for most of the remaining region associated with the transport corridor. The Circular Head Council is considering strategic plans to support its planning scheme, but such plans do not exist at present.

7.4 Additional Model Inputs

Table 7.4 sets out the main indicator interactions, their estimated e-folding response times, and the rule group weights. The new indicator changes are not weighted or constrained in any way. However, a more detailed assessment might consider the relative importance of the Road User group compared to the Local People group; and might also weight the sole indicator of biodiversity & physical environment more heavily than the two socio-economic indicators.

	Biodiversity/Env.	Road users	Local people
(ΔBio/ Env)^{old}	Positive: Weight = 1 1 year. Habitat fragmentation and spread of die-back, weeds, & feral species leads to more impact on biodiversity. Vegetation damage produces soil erosion and sediment degrades streams.	Positive: Weight = 1 1 year. Degraded habitat reduces aesthetic appeal of transport corridor to tourists.	Positive: Weight = 1 1 year. Degraded habitat and physical environment reduces livability of community, and degrades Aboriginal cultural links to the region.
(ΔRoad Users)^{old}	Negative: Weight = 1 2 years. More road users and off-road activities can degrade habitat and soil quality.	Positive: Weight = 3 1 year. More road users leads to more tourist support businesses (*e.g.* motels, shops, river cruises, and 4WD tour operators).	Negative: Weight = 2 1 year. More road users results in noise nuisance & safety concerns, and degrades Aboriginal cultural links to the region.
(ΔLocal People)^{old}	Negative: Weight = 1 2 years. Increased community size and activities can adversely impact habitat and species, and environmental quality.	Positive: Weight = 1 1 year. Increased community size requires more community support services, which also serve road users.	Positive: Weight = 2 1 year. Improved community livability results in stronger community and more non-road related business opportunities.
	ΔBio/Env^{new} Weight = 1	**ΔRoad Users^{new}** Weight = 1	**ΔLocal People^{new}** Weight = 1

Table 7.4 Dominant interactions, and their estimated e-folding times and weights.

In assigning the rule group weights, the $\Delta Bio/Env^{old} \rightarrow \Delta Bio/Env^{new}$ and the $\Delta(Road\ Users)^{old} \rightarrow \Delta(Road\ Users)^{new}$ interactions are expected to be naturally strong. The $\Delta(Road\ Users)^{old} \rightarrow \Delta Bio/Env^{new}$ and the $\Delta(Local\ People)^{old} \rightarrow \Delta Bio/Env^{new}$ interactions are judged to occur more slowly than the other interactions. Different interaction processes might be dominant in other road projects. For example, fewer animals and roadside trees improves road safety, but also reduce the attractiveness of the road, and its appeal to tourists. Similarly, the growth of a community within the transport corridor will provide more service to road users, but will also result in the community becoming more of a barrier to the road users.

The system of indicators set out in Table 7.4 has an overall e-folding time of about two years (the slowest interaction e-folding time), so the system should move to about 95 % of its new equilibrium some six years (three e-folding times) after the cessation of model forcing. This period usually corresponds to about 7 model iterations, or 8 time steps including the initial time step, and this is confirmed by preliminary model runs. Each time

step is thus about 9 months, which is roughly the duration of the road construction or upgrade period.

A reasonable approach to driving the model is thus to use impulse forcing, and Table 7.5 sets out the estimated set of initial indicator changes which occur over the nominal 9 month project period (a two decimal place accuracy is not intended to be implied in Table 7.5 - the discussion of changes was simply in terms of half and quarter values). The (negative) initial change for the *Local People* indicator denotes the fact that simply carrying out a road project is enough to diminish the region's heritage value to Aboriginal people.

	---------- *Initial indicator changes* ----------		
	Bio/Env	**Road Users**	**Local People**
Completion of Western Explorer	-0.25	+1.50	-0.25
Road upgrade, strong planning	-0.25	+2.00	+0.25
Road upgrade, weak planning	-1.50	+2.00	-1.00

Table 7.5 Model forcing by initial indicator changes.

7.5 Model Predictions

Table 7.6 summarises the model predictions for the three assessments, and the indicator change profiles are shown in Figure 7.6.

Considering the assessment of the link road completion, the model predictions agree well with the observed (estimated) indicator values. The number of time steps needed for the three fingerprint indicators to achieve 95% of the additional changes due to indicator interactions are as follows:

Biodiversity/physical environment	10 time steps
Road Users	3 time steps
Local People	6 time steps

This is consistent with the expectation of 8 time steps which was used in assigning the initial indicator changes that drove the model.

1. Link road completion.

	Baseline (1993)	*Observed (1998)*	*Model (1998/99)*
Bio/Physical Env.	9.0 (Excellent)	8.5 (Excellent)	8.7 (Excellent)
Road Users	4.0 (Poor/Okay)	6.5 (Good)	6.3 (Good)
Local People	7.0 (Good)	6.0 (Okay/Good)	5.8 (Okay)

2. Road upgrade with strong planning.

	Pre-upgrade	*Model (6+ years after upgrade)*
Bio/Physical Env.	8.5 (Excellent)	7.9 (Good)
Road Users	6.5 (Good)	8.6 (Excellent)
Local People	6.0 (Okay/Good)	5.4 (Okay)

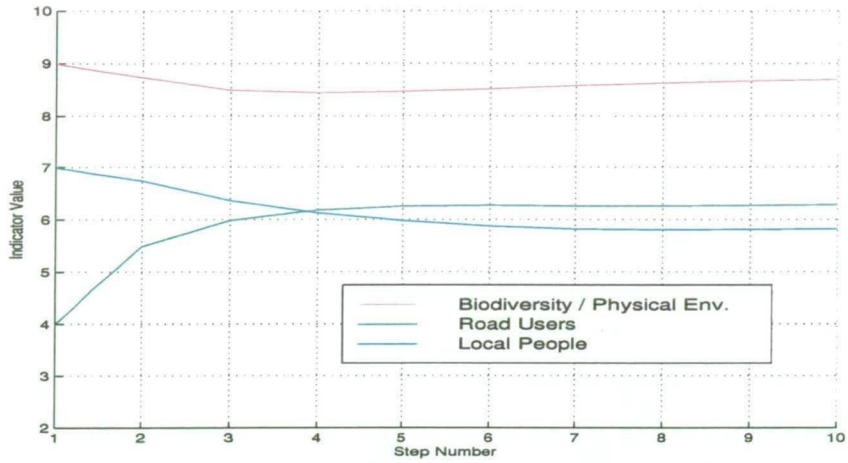
3. Road upgrade with weak planning.

	Pre-upgrade	*Model (6+ years after upgrade)*
Bio/Physical Env.	8.5 (Excellent)	7.3 (Good)
Road Users	6.5 (Good)	8.5 (Excellent)
Local People	6.0 (Okay/Good)	3.8 (Poor)

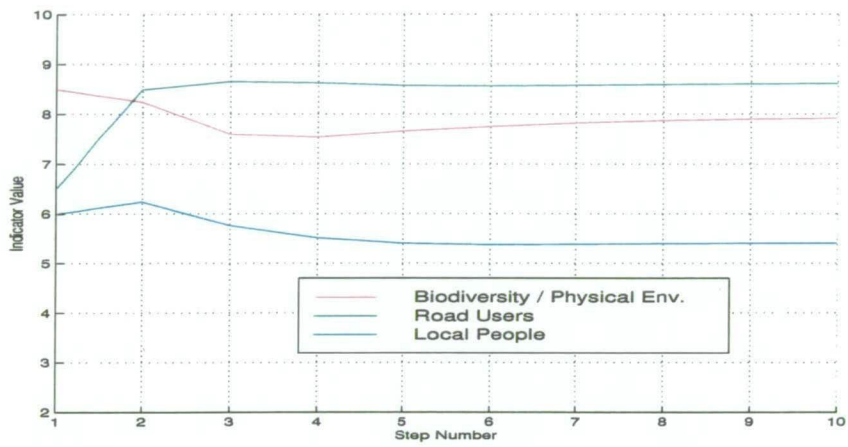
Table 7.6 Summary of predicted indicator changes.

Considering the two upgrade scenarios, the predictions are believable. A more detailed assessment might distinguish between the Aboriginal community and other local people, whose interests do not quite coincide regarding this project; and it might also distinguish between the biodiversity and physical environmental indicators. However, the relationships between these sustainability themes are not known well enough to justify such distinctions at this time. Furthermore, the conclusion of these comparative assessments is clear: any road upgrade should be carried out within the framework of a strong strategic plan.

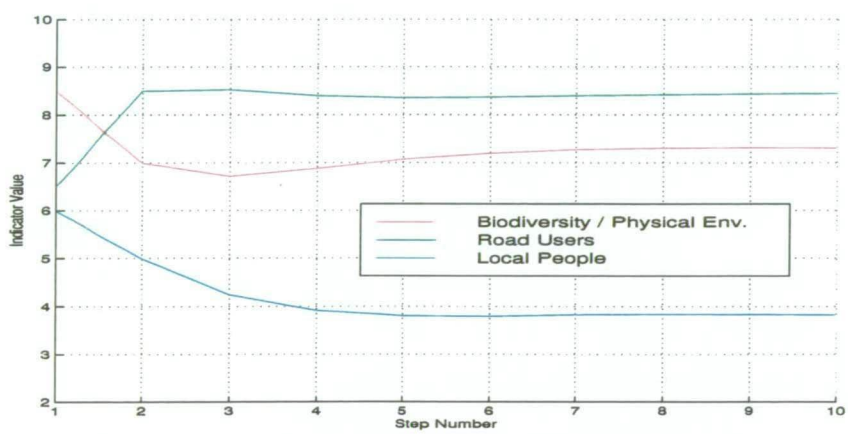
The assessment of a road upgrade subject to strong planning controls predicts a slight further degradation of environmental quality in the vicinity of the transport corridor due to an increase in the (strictly controlled) off-road recreational activities and road usage. Rental vehicle usage has increased significantly, and several coaches tours a month use the new route. The Local People indicator has again decreased slightly, primarily due to a further weakening of Aboriginal heritage links to the region. For other local people, regional community support services have slightly improved, but again there are also minor negative impacts such as road safety.



Impact of link road completion (1993-1998/99).



Impact of road upgrade with strategic planning controls.



Impact of road upgrade with no effective planning.

Figure7.6 Predicted indicator change profiles.

The assessment of a road upgrade subject to weak planning controls predicts a distinct deterioration of biodiversity & physical environmental quality, with adverse impacts due to sprawling road head development, new tracks appearing, and impacts from uncontrolled 4WD vehicles and other off-road activities. The present road-head communities of Arthur river and Corinna can be expected to grow, and new shacks would be built in the environs of the transport corridor. Coach and rental vehicle usage of road has further increased, but the general appeal of the region has diminished. The regional population has increased slightly, and community support services have improved, but Aboriginal heritage links to the region have significantly diminished.

An additional consideration is that the Department of Transport would have to address road safety and serviceability issues due to the remoteness of the transport corridor. For example, the risk of road surface failure is greater for a sealed road than for an unsealed road, since this latter simply becomes pot-holed. These technical and financial matters are not taken into account by the sustainability assessment, but instead act as constraints on decisions (see Chapter 8).

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8.0 PROJECT OPTION SELECTION

8.1 Introduction

This chapter examines classical and expert system approaches to the decision problem of selecting a preferred project option. The problem is either to pick one option from distinct variations on the basic project, or to determine the best values of one or more variable project parameters. It is assumed that the decision-making body behaves as an individual. Situations in which different decision-makers are involved, each with different goals, and each with access to different information upon which to base a decision, are not considered.

Decision goal

In the absence of constraints, the preferred project option is that which maximises positive sustainability indicator changes. The baseline indicator values must also be considered, since an indicator change with respect to a high baseline indicator value is less important than the same change with respect to a low baseline indicator value. This is a multiple-objective goal, since the indicators must be considered separately: it is not meaningful to relate some average indicator change to some average absolute indicator value.

To be fairly compared, the sustainability assessments of different project options should be based on the same geographic region, and the same period of time. The relative importance of the three sustainability themes (biodiversity, physical environmental and socio-economic) and their indicators must also be agreed. Human quality of life depends on all three themes, but sustainability visions differ between regions, as discussed in Chapter 2. Thus, a wilderness is managed according to a deep ecology vision, while heavy industrial zone planning decisions place less importance on biodiversity or physical environmental issues. Similarly, indicators within a theme may not have equal importance. For example, Road User and Local People indicators together describe the socio-economic aspects of a road transport project, but it may be agreed that one group has greater importance than the other (see the case studies in Chapter 7 and later in this chapter).

Decision constraints

Some project options may be unacceptable because they would result in unduly adverse sustainability impacts. For example, a project option that causes any of its sustainability indicators to fall into the *Bad* (0-2) region might be ruled out. In addition, the decision is subject to constraints which take the form of capital and operating costs, technical difficulty,

military significance, and so forth. These constraints may be associated with those attributes which define the project's basic nature (*e.g.* feedstock rate, fuel usage), and with mitigation measures, such as the type of pollution control equipment.

8.2 Decision Methods for Discrete Options

8.2.1 Benefit-Cost Analysis

Benefit-cost analysis (BCA) is the most used classical method of selecting a preferred project option. The basic method is described by numerous texts (*e.g.* Szonyi et al., 1982), and it has been tailored for application to many specific kinds of projects. For example, road planning exercises, such as the case study presented below, are often guided by Austroads (1996). BCA is primarily an economic analysis tool, and it is ideally applied when benefits and costs can be expressed as cash flows. This imposes a major limitation regarding the usefulness of the BCA method for strategic planning, since the here-and-now of market prices is not always a good basis for making long-term decisions. Furthermore, BCA is essentially a single-objective method, and cannot properly take into account externalities such as biodiversity issues.

8.2.2 Multi-Criteria Methods

Multi-criteria methods have been developed to provide better decision-making tools for use when a decision must consider externalities. Overviews of the subject are given by Bodily (1985), French (1988), and Nijkamp et al. (1990).

In practice, the selection of a preferred project option is usually based on ranking methods, such as a pairwise comparison of options, with an economic benefit-cost analysis included as one of the ranking criteria. Nijkamp et al. (1990) describe a variety of ranking methods.

Multi-criteria analysis methods (other than ranking methods) are rarely used to select project options. Tools such as mathematical programming are useful for many applications, such as manufacturing decisions, but they do not have the flexibility to address the range of criteria involved in strategic planning. The best known multi-criteria approach to including externalities in decision-making is based on the use of *utility,* rather than money. The approach is well described by Markland and Sweigart (1987), and by Lindley (1984).

Keeney and Raiffa (1976) provide several case studies, including air pollution control in New York City, and development of an airport to serve Mexico City.

In brief, utility is the preference a decision-maker has for an option, and the preferred project option is that which maximises expected utility. A utility analysis is ideal for a situation with m decision options, $d_1, \ldots, d_m$, and n possible outcomes, $\theta_1, \ldots, \theta_n$. A utility is assigned to each consequence, c_{ij}, that follows if decision d_i is taken, and outcome θ_j occurs. A utility is a probability, and can be assigned with reference to extreme consequences. Thus, the utility, u, of a consequence means that the consequence is just as desirable as a chance u of the most favourable consequence, or a chance $1-u$ of the worst consequence.

Formal utility analysis addresses the subject of risk, and provides two points of relevance to project planning based on sustainability impact assessment. First, sigmoidal utility functions are common, whereby decisions involving small pay-offs are associated with risk-prone decisions, and decisions involving large pay-offs are associated with risk-averse decisions. This philosophy is appropriate for project planning under conditions of uncertainty, since the precautionary principle requires that a conservative decision be made in the face of possibly large adverse consequences.

Second, utility analysis can readily use Bayes' theorem to calculate the value of additional information, for example to improve the estimate of a baseline indicator value (Lindley, 1984). The present assessment model can explore the sensitivity of model predictions to variations in baseline indicator values, or model forcing strengths, but it does not explicitly quantify the link between the uncertainty of its inputs and the variation in its predictions. Such a model extension would help determine the need for a conservative decision in light of the precautionary principle, and could guide efforts to reduce uncertainties in the input data.

8.2.3 Fuzzy Methods

Fuzzy logic is a natural decision-making tool, and the inputs to a set of fuzzy rules generates a decision surface for the rules (see chapter 3). Fuzzy versions of all the classic decision methods can be developed, and can provide a more natural approach to decision making involving externalities (Klir and Yuan, 1995; Terano et al., 1987; Zimmermann, 1991, and Fodor and Roubens, 1994). In road project planning, such as the case study presented later in this chapter, Australian transport authorities are actively pursuing fuzzy logic approaches to decision-making (*e.g.* NELA, 1998).

A simple example to fuzzy decision making is provided by a milk processing plant that was built in 1997/98 at a greenfield site on Tasmania's north coast. The author carried out an air quality study to support the development application, and provided advice on air pollution control equipment (Carter, 1996a; 1996b). The plant's power is provided by two 9.5 MW coal-fired boilers, which at full capacity burn fuel at a rate of 1,760 kg/h per boiler. Carter (1996a) determined that a simple cyclone system would allow the ambient air quality standard to be met, but recommended a multi-cyclone system in light of best practice expectations. An off-gas handling system consisting of a cyclone plus either a baghouse or an electrostatic precipitator would provide better gas cleaning, but with higher capital and operating costs, and a higher degree of operating difficulty.

The decision goal can be defined as minimising the equipment cost, under the constraints that the equipment is easy to operate, and the air quality decrease is small. A suitable air quality indicator would be the 99.9 percentile value of the ground level concentration of PM_{10} particulates, averaged over 24 hours. The key indicator values of 2 and 8, which define the start of the *Bad* and *Excellent* ranges, might be set at 90 $\mu g/m^3$ and 40 $\mu g/m^3$ respectively.

In practice, a fuzzy decision approach to this problem would use a software package such as MATLAB, and follow the techniques described in Chapter 3. First, membership functions would be defined to describe the three key variables: capital cost, operation, and air quality decrease. Then a set of expert rules would established, the extreme rules of which would be:

IF (cost is low) & (operation is easy) & (air quality decrease is small) THEN (preference is high)

IF (cost is high) & (operation is hard) & (air quality decrease is large) THEN (preference is low)

These rules illustrate an additional advantage of fuzzy decision methods, namely that there is no need to treat decision goals and constraints separately.

Fuzzy theory can also be applied directly to a set of discrete options, without developing a set of rules, using the method described by (for example) Klir and Yuan (1995). Table 8.1 lists the air pollution control equipment options (O1 to O5) considered for the milk plant's off-gas handling system, and the associated degrees of membership for the three decision variables, V1 to V3.

Equipment options	*V1. Capital cost*	*V2. Operation*	*V3. Air quality decrease*
O1. Stack only	$100,000 (0.9)	Very easy (0.9)	Very large (0.1)
O2. Cyclone	$200,000 (0.8)	Easy (0.8)	Large (0.3)
O3. Multi-cyclones	$300,000 (0.6)	Easy (0.8)	Fairly small (0.6)
O4. Wet scrubber	$600,000 (0.4)	Okay (0.6)	Small (0.7)
O5. Cyclone plus Baghouse/precipitator	$1 million (0.2)	Difficult (0.3)	Very small (0.9)

Table 8.1 Pollution control options, and fuzzy decision variable membership grades.

The fuzzy decision set, D, is obtained by picking the intersection (minimum operation) of the three membership values for each option, as follows:

Goal	V1 = 0.9 / O1 + 0.8 / O2 + 0.6 / O3 + 0.4 / O4 + 0.2 / O5
Constraint	V2 = 0.9 / O1 + 0.8 / O2 + 0.8 / O3 + 0.6 / O4 + 0.3 / O5
Constraint	V3 = 0.1 / O1 + 0.3 / O2 + 0.6 / O3 + 0.7 / O4 + 0.9 / O5
Decision	D = 0.1 / O1 + 0.3 / O2 + 0.6 / O3 + 0.4 / O4 + 0.2 / O5

Where "*X / Y*" denotes the grade of membership, *X* (0-1), associated with option *Y;* and the "+" signs join the five quantities as a set for each fuzzy variable (no addition is intended). As noted, there is no difference in the mathematical treatment of goals and constraints.

The most favourable decision is that with the highest membership value in the fuzzy decision set, in this case the multi-cyclone system, with a membership grade of 0.6.

8.3 Optimisation Methods

8.3.1 Classical Methods

The basic optimisation problem is to maximise or minimise a function, termed an *objective* function, usually subject to some constraints. An objective function is often termed a utility, although it need not be a probability (as is required by formal utility theory). There are three broad traditional approaches to solving such problems: calculus-based methods, enumerative methods, and random methods. These methods are described by many texts,

such as Spiegel (1971), Goldstein, (1959), and Kreysig (1993). Each method has found many applications, but also has its limitations.

Calculus-based methods are ideal if the solution to a problem can be expressed as the extreme value of some quantity that has a well-defined derivative. For example, the method of Lagrange multipliers finds the extreme values of a function $f(x,y)$ subject to constraint $g(x,y)$, while the calculus of variations aims to minimise an integral (a Hamiltonian, say) between two points in n-dimensional space. Gradient methods are also common, and the neural network training algorithms described in Chapter 4 used gradient descent methods to minimise the network error.

Enumerative methods, such as dynamic programming, determine the optimum solution to a problem by examining solutions throughout the entire n-dimensional solution space (defined by all possible combinations of the n variables upon which the solution depends). Such methods are straightforward, as are random methods such as the random walk, but are inefficient if the search space is large.

8.3.2 Genetic Algorithms

The genetic algorithm is an optimisation method based on the principles of natural selection. The concept was introduced and developed in the 1970s, primarily by John Holland and his students at the University of Michigan (Holland, 1973; 1975). Goldberg (1989) provides a good introduction to genetic algorithm theory, while Davis (1991) presents several case studies. Rooij et al. (1996) discuss the application of genetic algorithms to neural networks.

Figure 8.1 shows the basic genetic algorithm. In brief, the algorithm evolves an initial population of solutions, producing new generations of solutions until some termination criterion is satisfied. For the problem to hand, this criterion is that there is no significant change in the overall acceptability of successive generations of solutions. It is important to appreciate that the genetic algorithm is an optimisation method, but the final generation of solutions is only "optimum" in the sense that it satisfies the termination criterion. Also, the genetic algorithm may evolve a population of solutions towards one of perhaps many a local optima, of which one is a global optimum.

Genetic algorithms (GAs) have several characteristics which distinguish them from most classical optimisation methods (Goldberg, 1989; Chipperfield et al., 1995):

- GAs work with coded representations of the decision variables, not the decision variables themselves.

- GAs work with a population of solutions, not one solution.

- A GA is a stochastic process that does not need information such as derivatives in order to identify the optimum solution or solutions to a problem. Its only requirement is a way to evaluate how good a solution is provided by a given set of decision variables.

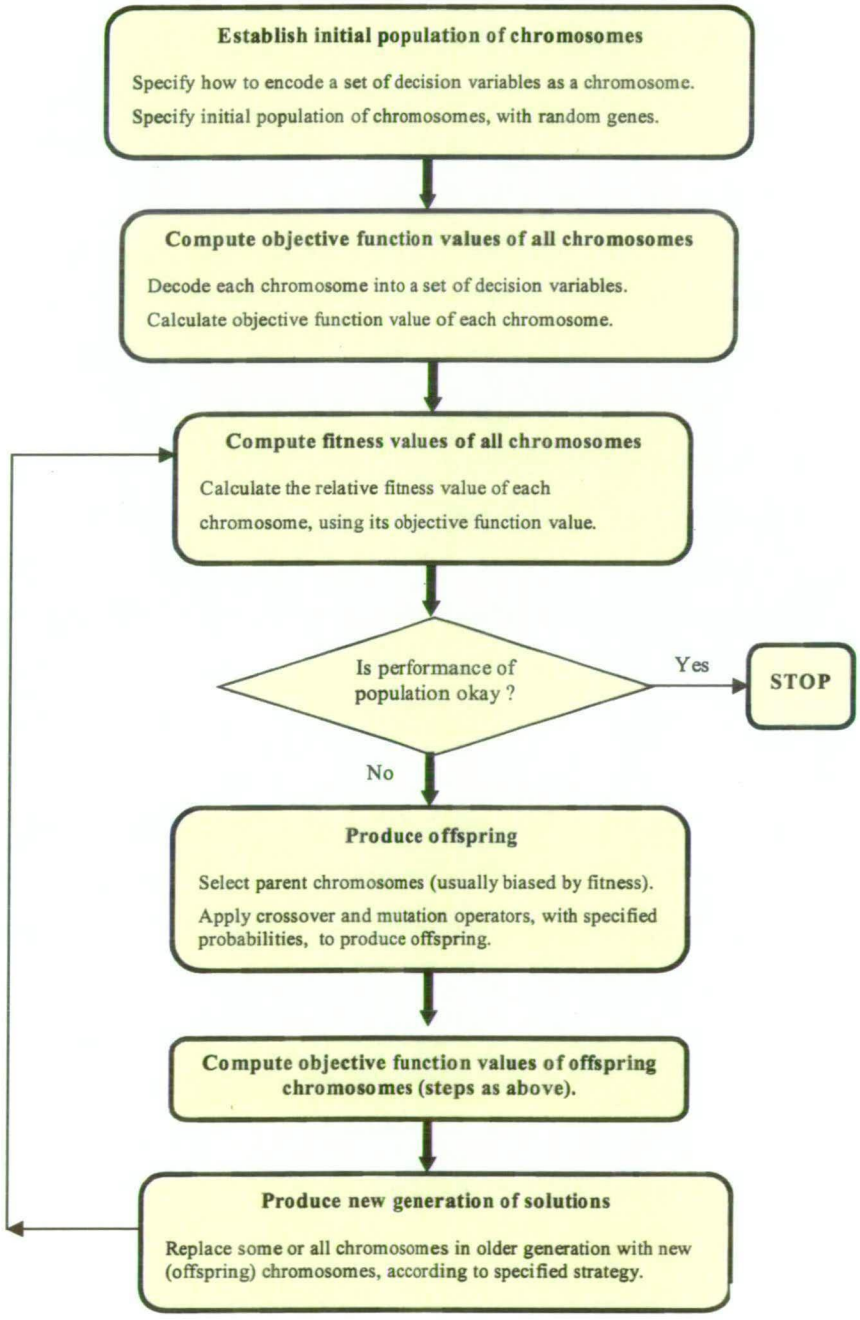

Figure 8.1 The basic genetic algorithm.

Initial population of solutions

A genetic algorithm considers a population of n solutions to a problem, $\{x_1, x_2, \ldots, x_n\}$. Each solution, x_i, is associated with a set of m decision variables, $\{v_1, v_2, \ldots, v_m\}$, and this set of variables is encoded as a *chromosome*. A binary string code is usually used, but integer, ternary, floating point and other codes are possible. For example, a solution which depends on two variables, v_1 and v_2, might be represented by the binary string shown in Figure 8.2 (Chipperfield et al., 1998).

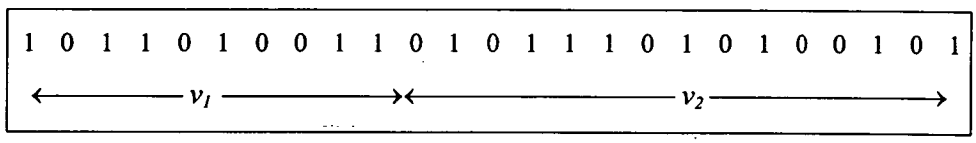

Figure 8.2 A 25-bit chromosome representing a set of two decision variables.

Variable v_1 is represented by the first 10 bits of the chromosome, and v_2 by the second 15 bits, with the number of bits reflecting the accuracy or range of the variables. Each bit in the chromosome represents a *gene* that can take on the value 0 or 1 with equal probability, and the initial population of chromosomes consists of randomly selected genes.

Evaluating the fitness of solutions

To assess the fitness of a given solution, x_i, its associated chromosome is decoded into its m component decision variables, $\{v_1, v_2, \ldots, v_m\}$. An *objective function*, $o(v_j)$, applies this set of decision variables to the problem at hand, producing some measure of the performance of the solution. A *fitness function*, f, transforms this measure into a non-negative relative fitness value:

$$\text{Fitness of solution } x_i = f[o(v_j)]$$

For example, the suitability of an animal to be a predator might be defined in terms of its strength, speed, intelligence. Strong, fast and clever animals will enjoy greater success as predators, and an objective function would provide a measure of this success, perhaps the percentage of attacks that result in kills. A fitness function then translates this performance measure into a relative fitness value, which in nature might manifest itself in terms of which animal becomes a pack leader.

As a general rule, the most difficult aspect of developing a successful genetic algorithm approach to an optimisation problem is encoding the decision variables into a chromosome. However, for the problem of optimising a set of variable project characteristics subject to

some constraint, a straightforward binary string encoding method can be applied. In this case, the specification of appropriate objective and fitness functions for the problem is the aspect of devising a successful genetic algorithm that requires the most attention.

Creating new solutions

A new pair of solutions is created by selecting two parent chromosomes, and applying genetic operators to produce two new chromosomes. Parent chromosomes can be selected in several ways, but usually the fitness values of the existing population of chromosomes are used to bias the chance that new chromosomes will be based on parent chromosomes with high fitness values. This is the *roulette wheel* selection method, and the probability $P(x_i)$ of selecting parent chromosome x_i, whose decoded solution has a fitness value $f(x_i)$, is:

$$P(x_i) = \frac{f(x_i)}{\sum f(x_i)}.$$

The principal genetic operators are the *crossover* and *mutation* operators. The crossover operator exchanges genetic information between two chromosomes, and it can be applied either at one point or at multiple points within each chromosome. The mutation operator changes a gene within a chromosome. In the case of a binary string chromosome, the gene change is $0 \leftrightarrow 1$. Many variations of these operators are described in the literature, and Figure 8.3 demonstrates typical forms (after Chipperfield et al., 1995).

Gene number	1	2	3	4	5	6	7	8
Parent 1	1	0	0	1	0	1	1	0
Parent 2	1	0	1	1	1	0	0	0
Crossover from genes 6 to 8.								
Offspring 1	1	0	0	1	0	0	0	0
Offspring 2	1	0	1	1	1	1	1	0
Mutation of second gene of offspring 1.								
Offspring 1	1	1	0	1	0	0	0	0

Figure 8.3 Typical gene crossover and mutation operations.

The crossover operation is applied to the parent chromosomes with a probability that is typically about 0.7, while the mutation operation is randomly applied to the offspring, with a

probability that is typically between 0.01 and 0.001 (Chipperfield et al., 1995; Davis, 1991). The crossover operation is fundamental to genetic algorithms, while the mutation operation acts as a safety net to recover good genetic material which is inadvertently lost through parent chromosome selection.

Establishing the new generation

A new generation of chromosomes is established by replacing parent chromosomes with some or all of their offspring, according to some replacement strategy. An obvious strategy is to replace the least fit members of the old population, which is an elitist strategy whereby the fittest solutions propagate through successive generations. (In the algorithm shown in Figure 8.1, the replacement strategy is based on the objective function values instead of the relative fitness values. This is simply a matter of convenience). A variation on the elitist strategy is to replace the oldest solutions, which assumes that younger solutions are usually better than older solutions.

The *generation gap* specifies the percentage of the new generation that are children of the previous generation, with the balance of the new generation comprising members of the previous generation.

8.4 Optimisation Case Study: Bruny Island Road Upgrade

8.4.1 Introduction

This case study illustrates a genetic algorithm approach to optimising a proposed road upgrade project on Bruny Island in southern Tasmania, based on upgrade issues identified by Carter (1995). The sustainability assessment of the project has been simplified in order to clarify the optimisation exercise. The nature of the project can be described by three factors (decision variables) that both influence sustainability issues, and that are associated with project capital and road maintenance cost constraints. Each decision variable is denoted by a parameter (α, β, and γ) that varies between zero and unity. The goal of the optimisation exercise is to determine the optimum combination of the three project factors.

Bruny Island has an area of about 355 km^2, and consists of two main islands connected by a 2.5 km long sandy isthmus, known as The Neck. As shown in Figure 8.4, The Neck separates the D'Entrecasteaux Channel to the west from Adventure Bay to the east. The

Channel is a shallow, sheltered body of water that lies between Tasmania and Bruny Island, while Adventure Bay extends out to the Southern Ocean.

The B66 road across The Neck is an unsealed part of the National Highway, and in places it is windy and narrow. Road safety concerns are significant, especially for recreational users of The Neck. The road is also prone to pot-holing, and requires frequent maintenance and regrading. This produces dust that disturbs the roadside vegetation, and leaves steep batters which act as barriers to wildlife, notably fairy penguins returning to their burrows.

Figure 8.4 The Neck of Bruny Island, looking south. The road lies on the west side of the isthmus, while high tide is obscuring the sandy beach on the east side.

8.4.2 Sustainability Assessment

Issues and indicators

For the purpose of illustrating the use of a genetic algorithm, the sustainability issues are assumed to be adequately described by only two indicators. The issues are similar to those identified for the Western Explorer road upgrade, described in Chapter 7.

Biodiversity/physical environment (Bio/Env) indicator. The Neck has a high quality physical environment, and excellent biodiversity with significant conservation value. The air is pristine, the sea is pollution-free, and only minor soil degradation is evident in the vicinity of the road. The east side of The Neck has a wide sandy beach, while its west side is sheltered and rockier. Sand dunes ridge along the axis of the isthmus, covered and

stabilised by dense scrub flora and grasses. The wildlife of The Neck and its adjacent wetlands are protected in a Game Reserve that includes colonies of fairy penguins (*eudyptula minor)* and mutton birds (*puffinus tenuirostris).* Other wildlife include the golden bellied water rat, and sea eagles.

Socio-economic (Soc) indicator. In 1998, Bruny Island had about 500 permanent residents, with holiday makers increasing the summer population tenfold, to over 5,000 people. The socio-economic indicator is an amalgam of the Road Users and Local People indicators, which together can describe the socio-economic aspects of most road projects (see Chapter 7). Road Users are those people who use the road primarily to travel across The Neck, including several truck operators who support the limited logging operations in the south part of Bruny Island. These people would tend to favour the highway upgrade option.

Local People are those who use The Neck for wildlife observation, and recreation. No-one lives on The Neck, but the Aboriginal community has close cultural ties to the region, which was home to a band of the South East tribe of Aborigines, and the area has many Aboriginal sites. The Local People group would favour an upgrade based on the existing alignment, providing a "scenic route" driving environment. South Bruny Islanders who serve the tourist industry view a sealed road across The Neck as necessary for better visitor access to south Bruny Island, but tend to be ambivalent about the form of the upgrade.

Indicator values and interactions

Table 8.2 gives the estimated baseline indicator values, valid for the mid-1990s, on the usual scale of 0 to 10, based on Carter (1995).

Bio/Env = 9.5 (Excellent).
Socio-economic = 5 (Okay).

Table 8.3 Baseline indicators (mid-1990s).

Table 8.2 sets out the principal indicator interactions, their estimated e-folding response times, and rule group weights, based on Carter (1995) and on the Western Explorer case study (Chapter 7). The system of indicators is expected to reach a new equilibrium some 6 years (3 x slowest e-folding time) after an initial impulse, such that each model time step is about 9 months.

	Biodiversity/Physical Env.	Socio-economic
$(\Delta Bio/Env)^{old}$	Positive: Weight = 2 1 year. Habitat destruction and fragmentation leads to loss of suitable nesting areas for seabird colonies, and reduces populations of terrestrial biodiversity. Vegetation loss produces dune erosion.	Positive: Weight = 1 1 year. Degraded habitat reduces recreation potential of The Neck, and degrades Aboriginal cultural links to the area.
$(\Delta Soc)^{old}$	Negative: Weight = 1 2 years. More road users and tourists can degrade habitat and soil quality, and impact wildlife.	Positive: Weight = 2 1 year. More amenities and safer road leads to more recreational usage of The Neck, and improves local tourist support businesses.
	$\Delta Bio/Env^{new}$ Weight = 1	ΔSoc^{new} Weight = 1

Table 8.2 Dominant interactions, and their estimated e-folding times and weights.

8.4.3 Decision Variables

The three decision variables are the extent of road upgrade (α), the extent of biodiversity and environment protection measures (β), and the extent of socio-economic provisions (γ). These parameters drive sustainability indicator changes, and also determine the project cost, which is the prime constraint on project viability.

Upgrade extent ($0 \leq \alpha \leq 1$). Sealing the existing alignment and keeping a design speed of about 60 km/h would provide a driving environment that primarily serves tourists and other recreational users of The Neck ($\alpha \approx 0$). Road re-alignment and widening would provide a driving environment suitable for road users passing across The Neck ($0 < \alpha < 1$) and, in the extreme, the road could be engineered as a full 110 km/h highway ($\alpha \approx 1$) with appropriate pavement quality and delineation. In general, a wider and faster road will require loss of habitat, will increase habitat fragmentation, and will tend to increase road kills. It will also require greater maintenance of the road surface, to ensure a safe driving environment.

Biodiversity/environment protection measures ($0 \leq \beta \leq 1$). Possible measures to protect and manage the local fauna, flora, cultural heritage and the environment include wildlife-friendly batters, fences to protect seabird colonies from tourists, wildlife tunnels and road-side "escape routes", speed controls, and restricted tourist beach access points. Values of $\beta \approx 0$ correspond to no protection measures, while values of $\beta \approx 1$ correspond to full measures.

Socio-economic provisions ($0 \leq \gamma \leq 1$). Provisions focus on amenities for users of The Neck, and include pull-over spaces along the road, upgrade of the small car-park, toilets, shelter, information boards, and more penguin viewing platforms. Values of $\gamma \approx 0$ correspond to no such provisions, while values of $\gamma \approx 1$ correspond to full provisions.

Impulse forcing is an appropriate approach to driving the indicator change prediction model, and Table 8.4 sets out the initial indicator changes estimated for extreme combinations of the project parameters. The initial *Bio/Env* indicator change is assumed to depend only on the extent of the road upgrade, and the extent of biodiversity/environment protection measures. Similarly, the initial *Soc* indicator change is assumed to depend only on the extent of the road upgrade, and on the extent of socio-economic measures.

Existing alignment ($\alpha \approx 0$)	$(\Delta Bio/Env)^{initial}$	$(\Delta Soc)^{initial}$
No measures ($\beta \approx 0$, $\gamma \approx 0$)	-0.5	+1.0
Full measures ($\beta \approx 1$, $\gamma \approx 1$)	0.0	+1.5
Highway alignment ($\alpha \approx 1$)		
No measures ($\beta \approx 0$, $\gamma \approx 0$)	-3.0	+2.0
Full measures ($\beta \approx 1$, $\gamma \approx 1$)	-1.5	+3.5

Table 8.4 Initial indicator changes for extreme project parameter values.

These initial indicator changes can be represented by the following functions, and Figure 8.5 shows the variation of initial changes with the road upgrade parameter, α.

$$(\Delta Bio/Env)^{initial} = f(\alpha, \beta) = -0.5 - 2.5\alpha + \beta(\alpha + 0.5)$$

$$(\Delta Soc)^{initial} = f(\alpha, \gamma) = 1.0 + \alpha + \gamma(\alpha + 0.5)$$

The total project cost is given by the (fictitious) cost function:

$$\text{Cost (\$K)} = 50 + 50\alpha + 30\beta + 20\gamma \qquad 0 \leq \alpha, \beta, \gamma \leq 1$$

The nominal base cost of the upgrade is \$50,000, which is an α=0 upgrade with no project improvement measures. Beyond this, the road upgrade cost, the cost of biodiversity and environmental measures, and the cost of amenities, are all assumed to vary linearly with the parameters α, β and γ respectively. For simplicity, it is assumed that the planning decision

only considers the capital cost of the project, but extending the analysis to include ongoing costs would be straightforward.

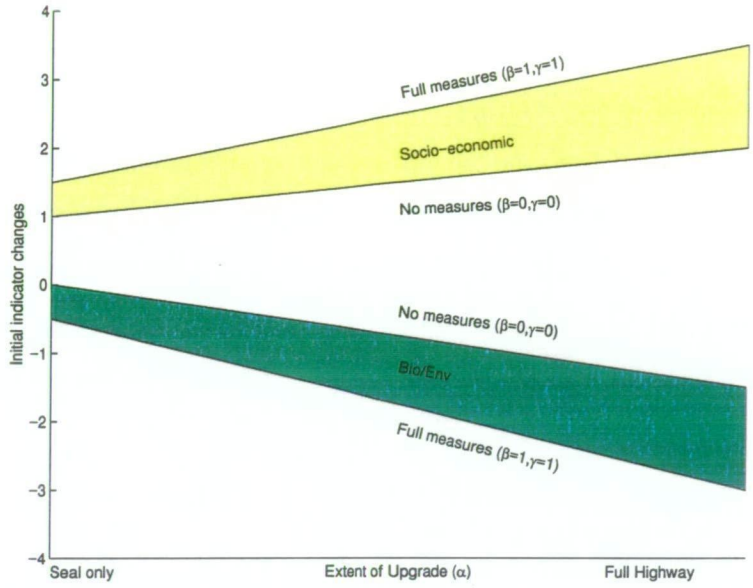

Figure 8.5 Variation of initial indicator changes with road upgrade parameter α.

8.4.4 Genetic Algorithm Design

A genetic algorithm suitable for solving the problem of "optimising" a set of project characteristics subject to come constraint can be based on a straightforward binary string encoding method. (As noted, the term a population of solutions is only optimal in the sense that the termination criterion is satisfied, and the solutions may correspond to a local optimum). For this kind of problem, the specification of suitable objective and fitness functions is the most difficult part of designing a successful algorithm.

The MATLAB genetic algorithm software described by Chipperfield et al. (1995) was used to develop the algorithm described in this section. Table 8.5 lists the key algorithm parameters.

Chromosomes	20 or 100	Generation gap	0.8
Generations	20 or 30	Crossover rate	0.7
Decision variables (α, β, γ)	1-3	Mutation rate	0.001
Bits per variable	16	Replacement strategy	Fittest

Table 8.5 Genetic algorithm parameters.

The three decision variables (α, β, and γ) are real numbers between 0 and 1, and each is represented by a 16-bit binary string. The genetic operators are applied with (the typical) probabilities of 0.7 for the crossover operation, and 0.001 for the mutation operation.

The number of decision parameters depends on whether any parameters are constrained to specific values, while the number of chromosomes and generations required depends on whether the algorithm is searching for one solution or a range of near-optimum solutions. A population of 20 members (chromosomes) is used when the fitness function is such that only one optimum solution exists, and 20 generations is sufficient to allow all members of the population to converge to this solution. A population of 100 members is used when the fitness function is such that all solutions with a specified minimum fitness are considered to be optimum. Evolving this population over 30 generations is sufficient to identify the spread of acceptable solutions. A generation gap of 0.8 is used: for a population of 20 members, a generation contains 16 new members, and the 4 fittest members of the previous generation.

The objective function ("utility") consists of sustainability and project cost components. The sustainability utility of a given indicator is here defined as its final value (baseline plus change), as predicted by the assessment model. Both sustainability and cost utilities are converted to a scale of 0 to 10, and their profiles are shown in Figures 8.6 and 8.7.

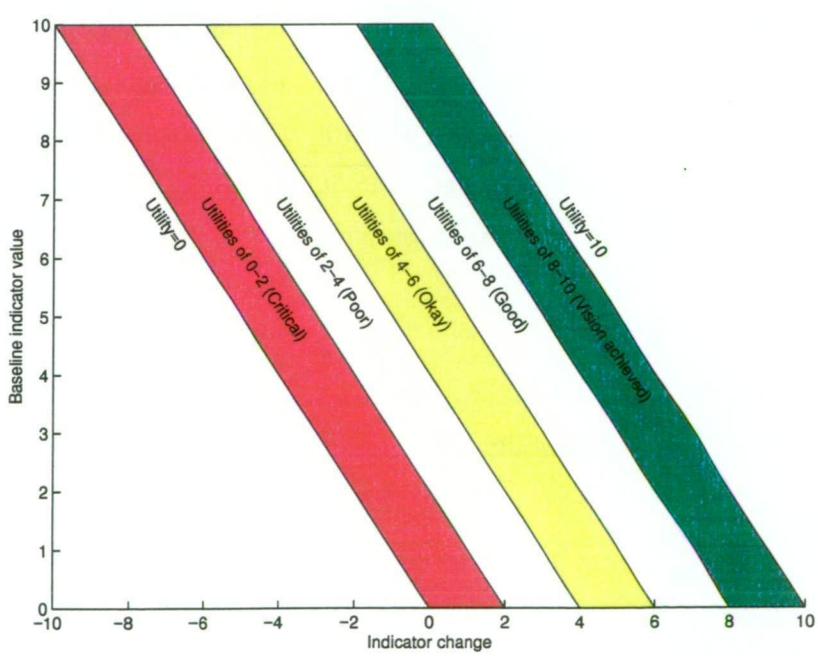

Figure 8.6 Sustainability utility values, here set equal to the final indicator values.

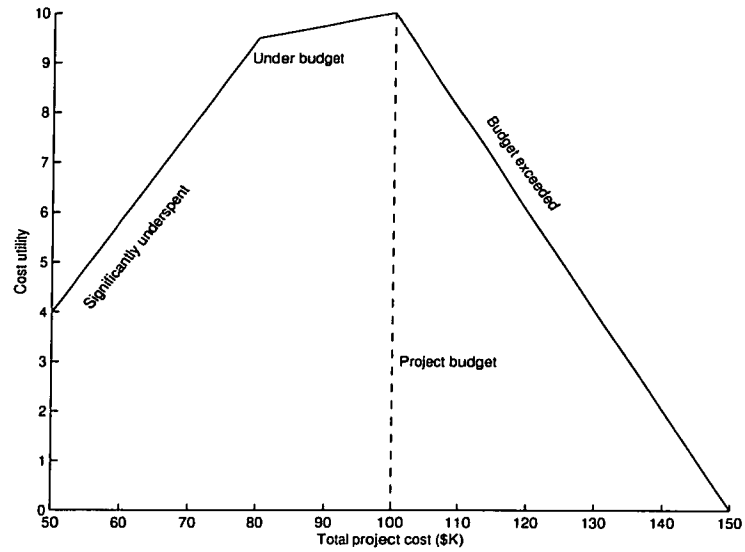

Figure 8.7 Project cost utility. A $50,000 cost corresponds to the $\alpha = \beta = \gamma = 0$ upgrade, and a $150,000 cost to the $\alpha = \beta = \gamma = 1$ upgrade.

The overall project sustainability utility is defined as the average of the two component sustainability indicator utility values. Other definitions might be agreed, and aggregation weights may need to be specified if the indicators have different degrees of importance. One safeguard, that is not necessary for the range of final indicator values associated with this project, would be to set the sustainability utility to zero if either of the final indicator values is in the *Bad* range (0-2).

The rationale for the cost utility profile shown in Figure 8.7 is that a project cost of $100,000 (say) has been allowed for in the transport authority's annual road budget. Any project in the range of $80,000 to $100,000 has a high cost utility, with a $100,000 project cost being optimum (cost utility = 10). A project cheaper than $80,000 has a lower cost utility, since the transport authority is expected to spend its annual budget. A more expensive project also has a lower cost utility, since this places the annual budget in over-run.

The fitness function is specified to be the weighted sum of the two objective functions (*i.e.* the project sustainability utility and the project cost utility), and ranges from 0 to 10:

$$\begin{aligned} \text{Fitness} &= w_1\,[\text{Sustainability utility}] + w_2\,[\text{Cost utility}] \\ &= w_1\,[k_1\,(\Delta\text{Bio/Env})^{\text{final}} + k_2\,(\Delta\text{Soc})^{\text{final}}] + w_2\,[\text{Cost utility}] \\ &= 0 \qquad (\Delta\text{Bio/Env})^{\text{final}} < 2 \text{ or } (\Delta\text{Soc})^{\text{final}} < 2 \end{aligned}$$

where w_1 and w_2 are weights applied to the two fitness components, and k_1 and k_2 are weights applied to the two sustainability indicators. The values $w_1 = w_2 = k_1 = k_2 = ½$ are used, since there is no reason to specify unequal weights for this project.

In order to bring near-optimum project options to the attention of the decision maker, the fitness function should be modified such that all solutions with at least a certain level of fitness are assigned a maximum fitness. For example, if a decision maker is interested in the best 10 percent of solutions, then:

$$\text{If Fitness} \geq 90\% \text{ Fitness}^{max} \rightarrow \text{Fitness} = \text{Fitness}^{max}$$

8.4.5 Predictions

An optimum solution is easily determined if only the road upgrade parameter, α, can vary, and the parameters denoting the extent of biodiversity/physical environmental measures and social amenities, β and γ respectively, are fixed. Figure 8.8 shows the variation of fitness functions with road upgrade parameter α for three benchmark cases: no project improvement measures ($\beta = \gamma = 0$); halfway measures ($\beta = \gamma = ½$); and full measures ($\beta = \gamma = 1$).

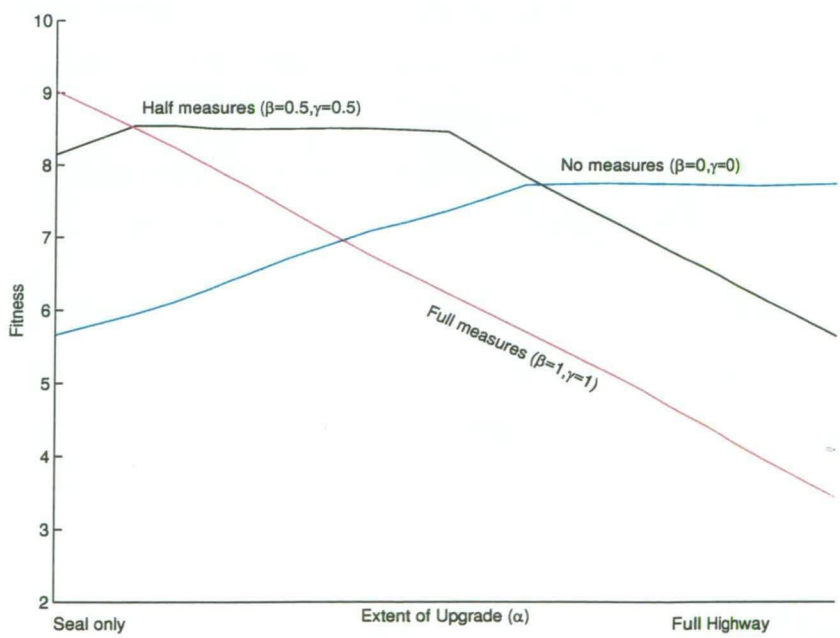

Figure 8.8 Variation of solution fitnesses with road upgrade parameter, α, for three cases in which decision parameters β and γ are held constant.

The half-measures case has an optimum value of $\alpha = 0.13$, and all values of α between about 0.1 and 0.5 are close to this optimum value. The no-measures case has an optimum value of $\alpha = 0.70$, and all values of $\alpha > 0.7$ are near to this optimum value. The optimum value of α for the full-measures case ($\beta = \gamma = 1$) is $\alpha = 0$. Examination of the neighbourhood of the point $\{\alpha = 0, \beta = 1, \gamma = 1\}$ indicates that this combination of decision variables is in fact the best solution for the project overall, with project sustainability and cost utilities of 8.05 and 10.00 respectively, giving an overall solution fitness of 9.02.

Half-measures case ($\beta = \gamma = ½$).

Considering the half-measures case, Figure 8.9 shows the variation of final sustainability indicators with the upgrade parameter, α, and the corresponding sustainability utility values (the average of the two final indicator values). Figure 8.10 shows the variation with α of the sustainability and cost utilities, and the fitness values obtained by averaging the two utilities.

Six runs of the genetic algorithm predicted the following optimum values of the parameter, α: {0.1339, 0.015, 0.1070, 0.0162, 0.0730, and 0.1702}, with a mean value of α_{mean}=0.086. In each case, convergence to a single optimum value common to all members of the population occurred within 15-20 generations. Figure 8.11 shows the variation in the genetic algorithm's prediction of the optimum value of α for the first run ($\alpha = 0.13$). It is impressive that the genetic algorithm is able to identify the true optimum value with reasonable accuracy, but it is necessary that values of α which are close to optimal are also brought to the attention of a decision-maker. As noted, this can be accomplished by modifying the fitness function such that all solutions which are close to optimum are treated equally, by assigning them all maximum fitness values.

Figure 8.12 shows the near-optimum solutions to the half-measures case when all fitness values over 0.84 are assigned maximum fitnesses. The modified genetic algorithm considers a population of 100 members, evolved over 30 generations. The solutions range from $\alpha = 0.09$ to $\alpha = 0.44$, which is in good agreement with the range of near-optimum solutions shown in Figure 8.10.

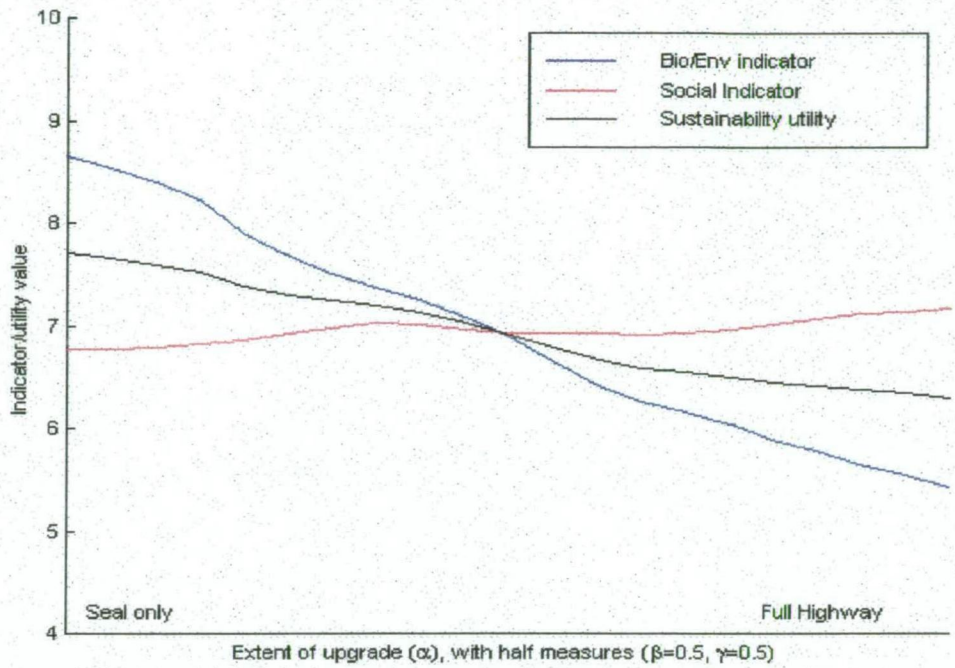

Figure 8.9 Variation of final sustainability indicators with road upgrade parameter, α, for the half-measures case (β = γ = ½).

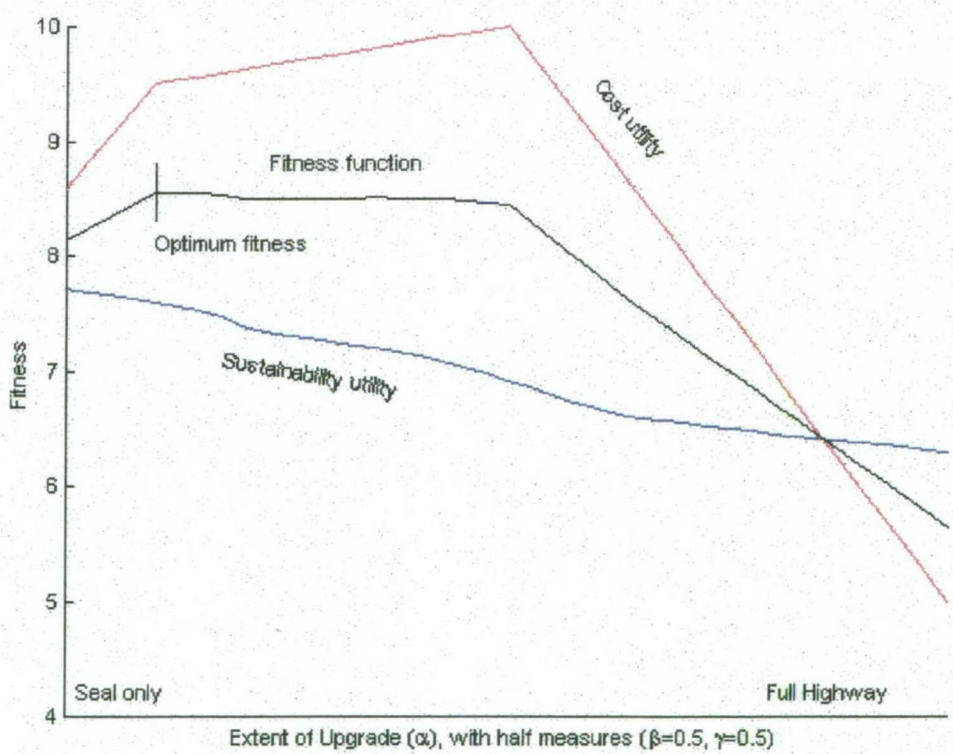

Figure 8.10 Variation of project sustainability and cost utilities, and solution fitness, with road upgrade parameter, α, for the half-measures case (β = γ = ½).

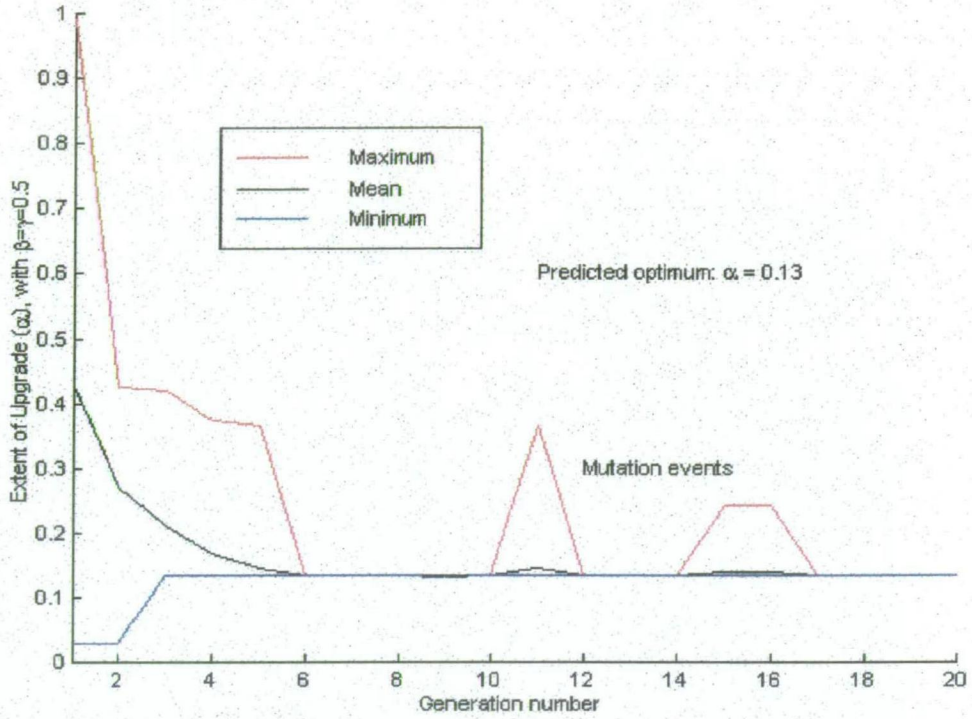

Figure 8.11 Genetic algorithm determination of the optimum value of road upgrade parameter α, for the half-measures case (β = γ = ½).

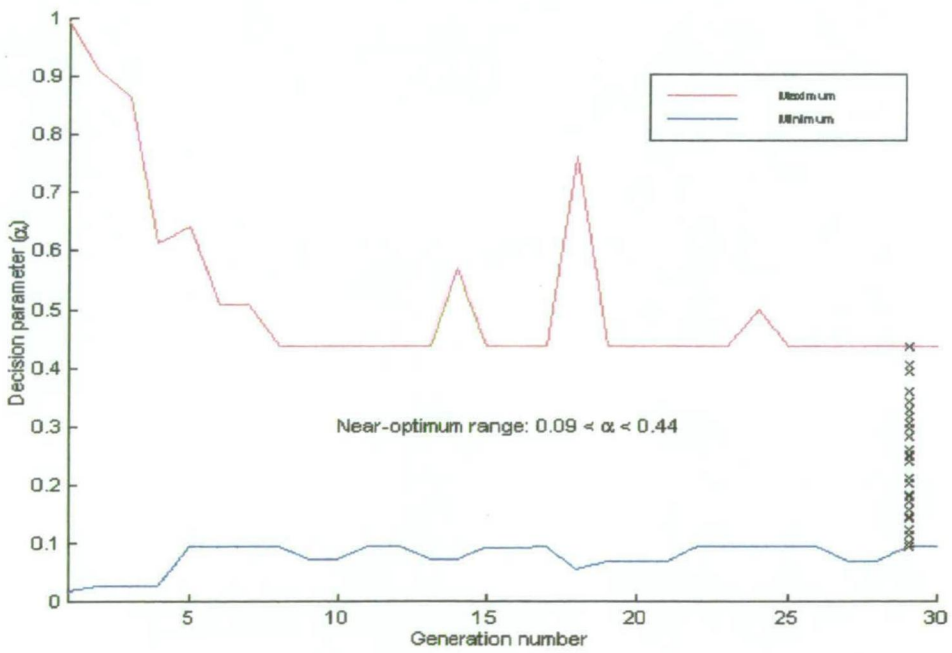

Figure 8.12 Genetic algorithm determination of near-optimum values of parameter, α, for the half-measures case (β = γ = ½). Solutions are shown as crosses.

No measures case ($\beta = \gamma = 0$).

Application of the genetic algorithm to the no measures case found an optimum value of α_{mean}= 0.70, averaged from the six predictions α: {0.6874, 0.7088, 0.7001, 0.7017, 0.7191, and 0.6994}. Figure 8.13 shows the variation in the genetic algorithm's prediction of the optimum value of α over 20 generations for the first run (α = 0.69).

As before, the genetic algorithm has identified the true optimum value, but fails to bring near optimum values of α to the attention of a decision-maker. Figure 8.14 shows the range of near-optimum solutions found when all solutions with fitness values over 0.76 are assigned maximum fitnesses. As before, the modified algorithm considers a population of 100 members, evolved over 30 generations. The near-optimum solutions are $0.60 < \alpha < 0.91$, which agrees quite well with the range of near-optimum solutions shown in Figure 8.10.

Free variation of parameters

As noted, the {α =0, β = 1, γ = 1} combination of parameters is the overall optimum for the project, with a fitness value of 9.02. However, a number of other combinations of parameters have near-optimum fitness values. Figure 8.15 shows the near-optimum (fitnesses > 8.8) ranges of decision parameters α, β, and γ, predicted by the modified genetic algorithm, with 100 solutions evolved through 30 generations. Overall, the best road upgrade project is predicted to be one which simply seals the road and follows the existing alignment; and which provides good environment protection and social amenities.

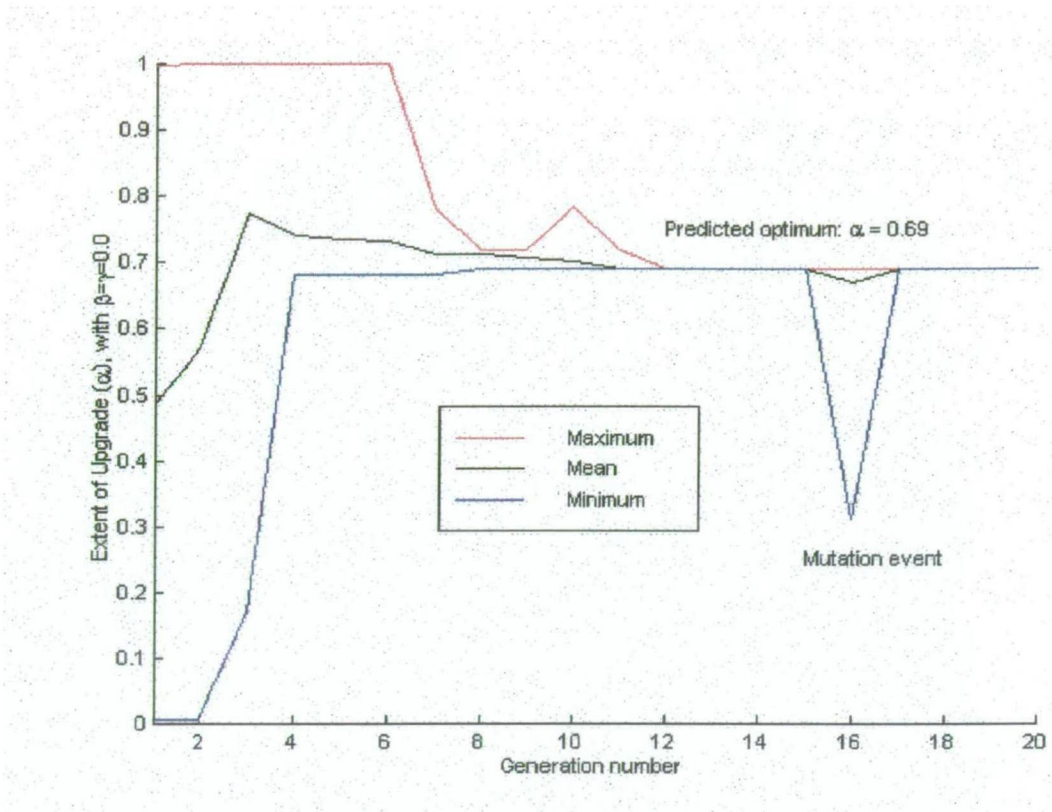

Figure 8.13 Genetic algorithm determination of the optimum value of parameter, α, for the no-measures case (β = γ = 0).

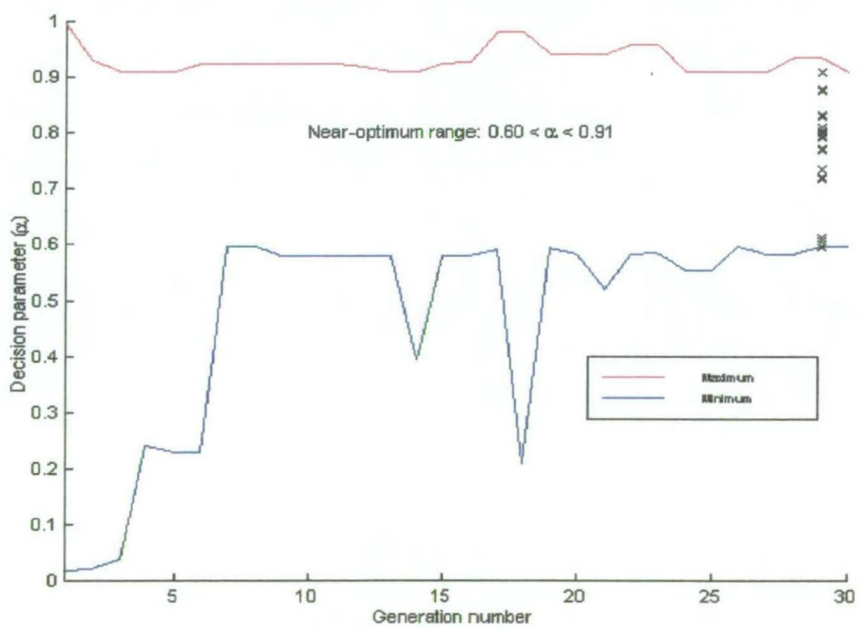

Figure 8.14 Genetic algorithm determination of near-optimum values of parameter, α, for the no-measures case (β = γ = 0). Solutions shown as crosses.

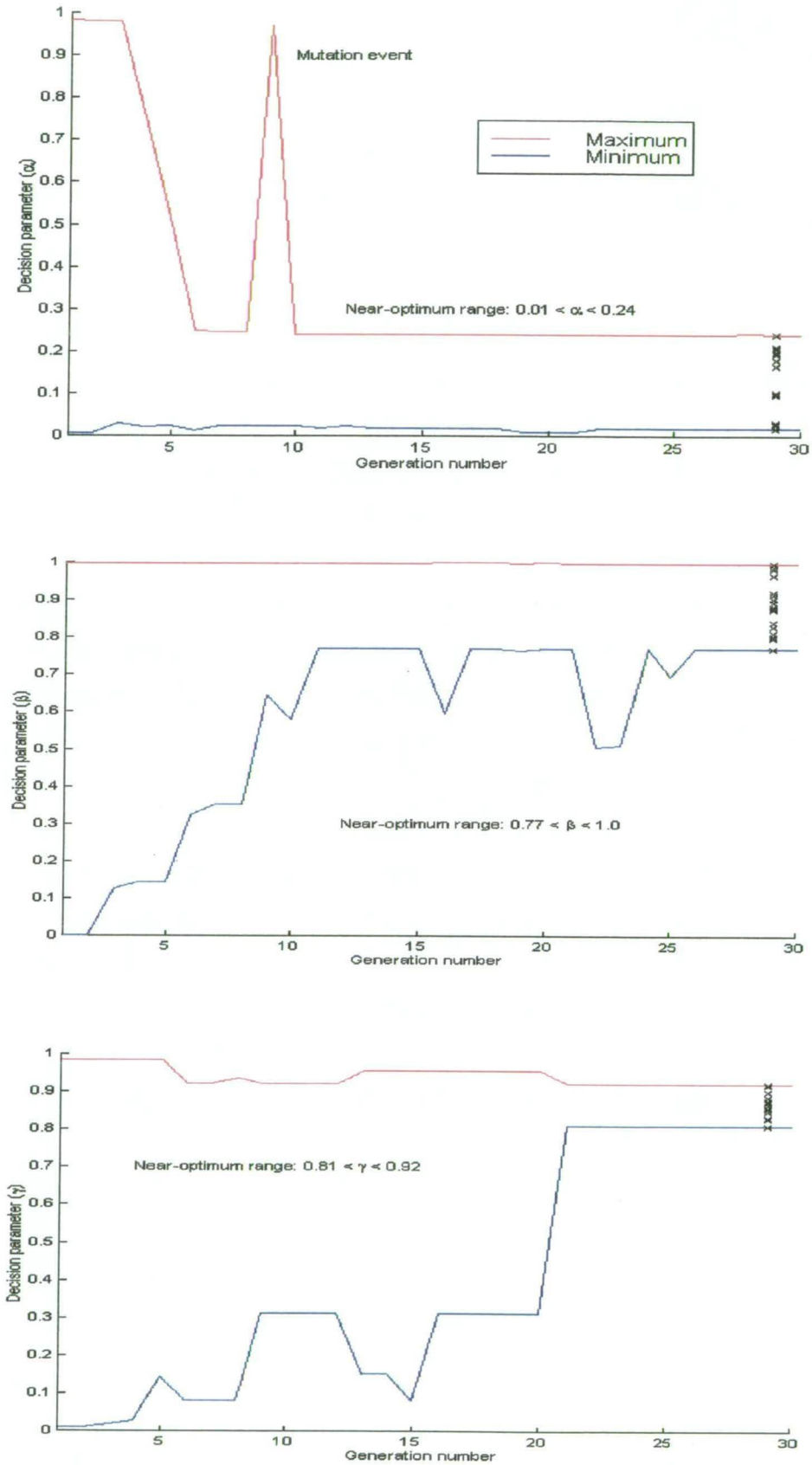

Figure 8.15 Genetic algorithm determination of the near-optimum values of all three decision parameters, α (top), β (middle), and γ (bottom).

8.5 Discussion

This chapter has examined classical and expert system (fuzzy logic and genetic algorithm) approaches to the decision problem of selecting a preferred project option. Project option selection to date has largely relied on benefit-cost analysis: multi-criteria methods that include non-monetary externalities in the decision-making process are rarely used in practice, with the exception of simple ranking methods.

The decision problem is to maximise the positive sustainability impact of a project, while taking into account constraints in the form of project costs, technical difficulty and so forth. Sustainability impacts are defined by the indicator changes caused by a project, with consideration of the baseline indicator values and, in general, each sustainability theme and its indicators must be considered separately.

For cases in which the project options are discrete, fuzzy decision methods offer a natural and easy way to include externalities, and industry interest in these methods is high (*e.g.* NELA, 1998). For cases in which one or more project parameters vary, the use of a genetic algorithm to identify ranges of acceptable solutions provides a useful alternative to classical optimisation methods.

Fuzzy methods and genetic algorithms do not differentiate in their treatment of decision goals and constraints. For the problem of optimising a set of project characteristics subject to some constraint, a straightforward binary string encoding method can be applied, and the specification of objective and fitness functions is the most difficult part of designing a suitable genetic algorithm. Beyond this, the only note of caution is that the genetic algorithm design should allow it to identify near-optimum project solutions, in addition to the absolute optimum solution.

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9.0 RESEARCH RESULTS AND OUTLOOK

9.1 Research Results

The principal outcome of the research reported in this thesis is the development and verification of an assessment method that provides a way to systematically evaluate the sustainability impact associated with a project. The new tool will appeal to environmental professionals and to strategic planners, especially in light of the increasing need for a strategic approach to resource management planning.

Based on a review of our current understanding of sustainability, it was decided that the best basis for designing an assessment method would be to organise sustainability issues into biodiversity, socio-economic, and physical environmental themes, and that each theme should be quantified by a cohesive set of indicators. This approach matches the way in which planners think about project externalities, and commission specialist studies. It also builds on the widely used State of the Environment reporting process.

It was recognised that the use of aggregation methods to condense indicators into indices would provide a more concise description of sustainability issues, and hence make the assessment a more practical planning tool. Fuzzy rule systems were developed and applied to case studies, and shown to provide a natural and powerful alternative to classical aggregation techniques for situations in which the relationships between the indicators and the index they support are reasonably well understood. Similarly, backpropagation neural networks were applied to case studies, and shown to provide a natural and powerful alternative to regression analysis for situations in which the aggregation of indicators relies on data pattern recognition.

A key part of the assessment method is its ability to predict indicator changes, and hence quantify the sustainability impact of a project. The prediction problem was found to be similar to climate modelling, but it was appreciated that a traditional modelling approach would face several difficulties that the expert system approach might overcome. The major barriers to a traditional approach are that the equations governing regional sustainability issues are unknown, and the indicators are often measured by best-guess information.

A new approach to the prediction problem was developed, based on a fuzzy rule model, and using MATLAB computing software. Interactions between the indicators are computed iteratively, and a variety of model forcing methods can be applied. The modelling approach is intuitively reasonable, and a suite of model performance and sensitivity tests show that the model is well behaved.

A further departure from a traditional modelling approach is to measure sustainability indicators on a scale of 0-10, interpreted in terms of the five ranges {*Bad* (0-2), *Poor* (2-4), *Okay* (4-6), *Good* (6-8), *Excellent* (8-10)}, where a *Bad* indicator value denotes criticality, and an *Excellent* indicator value denotes achievement of the sustainability vision. It is more usual to use natural units to measure quantities, but the alternative approach facilitates both the assignment of indicator values, and their interpretation in a planning context. The use of fuzzy rules, rather than differential equations, enabled the alternative approach to measuring variables to be successfully applied.

Practical case studies were carried out, involving primary industry and road transport planning projects. The model predictions of indicator changes compare well to expectations, and even fairly crude modelling approaches provide clear conclusions about the sustainability impact of projects. The assessment method is shown to be particularly effective when used as a tool to compare project options.

The assessment method developed by this research takes into account that adverse project impacts can mitigate or avoided by provision of environment protection, biodiversity management, and socio-economic measures. The financial or technical aspects of project options and impact mitigation measures provide constraints on viable solutions. The thesis concludes by showing how decision-making methods can take such constraints into account. A fuzzy decision method is applied to the problem of selecting a preferred project option from discrete alternatives, and a genetic algorithm approach is used to optimise a project with respect to its key variables.

9.2 Outlook

An exciting aspect of this thesis is its exploration of artificial intelligence tools. Fuzzy rules, neural networks, and genetic algorithms have great potential to be applied to many environmental problems, although the relative merits of traditional methods for a given problem should always be considered. There are many possibilities for further research into the use of artificial intelligence in decision making. Game theory is one aspect of decision

making that has not been examined by this thesis, but which in the opinion of some workers may prove to be important in arriving at sound resource planning decisions. Also, ways must be found to better take into account the importance of the heritage ("spiritual") aspects of the socio-economic sustainability theme.

Good regional sustainability data are not yet available, and the model cannot be exhaustively validated at present. However, our understanding of sustainability, and how to measure it, is improving rapidly. There is much cause for optimism that the present sustainability assessment model will be improved in the near future.

- Indicators are being developed and monitored for State of the Environment reporting. This will allow better input to sustainability assessments, better understanding of the indicator interactions, and a basis for refining the modelling approach.

- There is increasing agreement regarding what indicator values constitute *Excellent* (sustainability vision achieved) and *Bad* (intervention needed). There is an ongoing convergence of physical environmental standards; we are becoming better at measuring biodiversity; and socio-economic expectations are being set with awareness of international and national benchmark standards.

- The use of geographic information systems, remotely sensed information, and computer databases is increasing. At the same time, desk-top computers and supporting software packages are becoming better able to process such information. This improved ability to examine "the big picture" facilitates the implementation of resource management policies.

- State and Local governments are improving the consistency of their approaches to planning decisions, as planning schemes are modified to better take into account neighbouring schemes, and strategic regional goals.

Engineers and planners have become very aware of the need for environment protection, and environmental engineering is a well established discipline. Beyond environment protection, there is now widespread commitment to sustainability, which is a more strategic imperative. People have struggled to come to terms with what practicing according to a sustainability ethic means for specific projects, and it is the author's hope that this thesis will help to overcome this problem.